THE CAUSE OF UNSATURATION IN COLOR PERCEPTION

INCLUDING

AN EXPERIMENTAL STUDY OF ANOMALOUS TRICHROMATIC VISION.

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Being a thesis presented to the Department of Physics in the University of Manitoba in partial fulfillment of the requirements for the Degree of Master of Science.

University of Manitoba

April, 1926.

SYNOPSIS

Part I

The graphical representation of the perception of colors.

Introduction.

A. In section A a slight résumé of the theory of Young and Helmholtz is given.

B. In section B certain results of Abney and Allen's work are given to show the possibility of representing the formation of color sensations graphically.

In this section the following points will be discussed:

(1) The white light underlying all color sensations.

(2) Why more white light underlies color sensations other than the primary ones.

(3) Green has no spectral complementary and can not produce white with any other single sensation. Colors which give white when mixed must have in their component make-up three primary colors, red, green, and blue.

(4) The stimulation of the red sensation by waves of the violet region.

(5) Reasons for assuming the primary blue sensation is not the ordinary blue found in the blue region of the spectrum.

(6) Why white light is seen when the eye is stimulated with a single dazzling color, and also why green is the last color to be seen at low intensities.

Part II

A. Sensation curves by the Flicker method.

B. Anomalous Trichromatism.

C. Apparatus and methods of observation.

D. Curves and data.

INTRODUCTION

The perception of color is a subject which has probably caused more speculation than any other branch of science. Theories regarding the origin of color and the nature of its perception date as far back in history as the time of the early Greek Philosophers. But despite manifold attempts on the part of these early scholars to explore this fascinating field, the subject lay wrapped in mystery until Newton with his prism dispersed white light into its color components. Once it became established that white light was a mixture of colors, progress became rapid and certain.

It is scarcely to be wondered that every theory of color vision is far from being complete; the changes which take place in a visual reaction, are changes whose interpretation requires extensive knowledge of Physics, Physiology, Chemistry and Psychology. It is not surprising then, that the subject presents so many complex features.

The main controversy today is between the theory of Hering and that of Young modified by Maxwell, Helmholtz, Abney, Allen, and others. This latter theory adopted generally by Physicists, provides for three color sensations, red, green, and blue; while the theory of Hering adopted largely by Psychologists provides three antagonistic pairs of color sensations: red-green, yellow-blue and white-black.

THE GRAPHICAL REPRESENTATION OF THE PERCEPTION OF COLORS.

This method of showing how our color sensations are formed is based on the Young-Helmholtz Trichromatic Theory of color vision, the sensation curves of Abney and Watson, and the experimental and theoretical considerations of Allen's work on reflex visual sensations.

Section A.

THE YOUNG-HELMHOLTZ TRICHROMATIC THEORY OF COLOR VISION.

The mixture of Pure Color Stimuli. (1)

The Young-Helmholtz theory of color vision is based upon the facts of the mixture of pure color stimuli. The fundamental laws of color mixtures were first stated by Grassmann in 1853. They are as follows:

(1) Unlike lights mixed with like lights produce unlike mixtures, or if in a mixture one component is continuously altered the appearance of the mixture will also continuously alter.

(2) Like lights mixed with like lights produce like mixtures, or if two lights that look the same are each mixed with a third light the resultant mixtures will look alike.

(3) Every mixture of lights can be matched by a definite spectral light or a definite purple mixture which is mixed with a definite amount of white light, or if we take any fixed homogeneous or composite light and mix it with the whole series of pure spectral lights, completed by purple, varying the proportions in the mixture from zero of one to zero of the other, we obtain every known variety of stimulus.

The importance of these laws is that matches of optical mixtures resemble algebraical equations and can be treated as such, the match holding good if any addition or subtraction is made to both optical mixtures.

(1) Parsons - Color Vision.

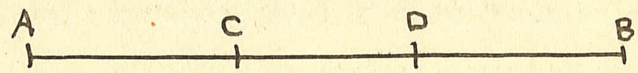
If a pure spectrum from an arc light of moderate intensity is observed a band of colors is seen; of these, four are clearly defined as separate and distinct from each other; viz., red, yellow, green, and blue, the red region consisting of the least refracted rays, the blue the most refracted. The gradation from red to yellow is gradual and passes through the orange region, the red gradually diminishing and the yellow increasing in a direction passing towards the yellow. Between yellow and green a similar gradation occurs, the yellow becoming more and more tinged with green until no yellow can be recognised and the color gives the impression of pure green. Passing further towards the blue an intermediate green blue region is met with showing the same gradual transition until the blue no longer gives any impression of green. Beyond the blue a region occurs which is still of the order "blue", but is not pure blue. It is called violet, a color which rarely occurs in nature. There is, however, a color in nature which is often called violet, but which is really purple. True purple does not occur in the spectrum, but it can be obtained by mixing pure blue light with pure red light, and we can thus pass from blue to red through violet and the mixtures of blue and red which are called purple and carmine.

Thus a complete circle is formed, and it is possible to return to the original starting point, i.e., red. This is a very important fact, for it can be proved with the help of the colors thus obtained, either pure or mixed with each other or with black in various proportions all known colors and tints can be reproduced.

The progress from red to violet via purple must be represented by a straight line, for experiment shows that purple can only be obtained by mixing red and violet, and therefore any purple must be made up of more or less parts of violet and red. Therefore a straight line joining the points which represent the Red and the Violet must contain the points which would represent any combination of these two colors, that is any purple.

For example, take the region between 600 μμ and 540 μμ. All the color sensations in this region made up of mixtures of these two colors Red and Yellow can be matched with a color sensation derived from some spectral color between these points. For red passes gradually by addition of yellow through the orange region until it is no longer apparent as red, but is perceived as yellow, hence by varying the proportion between pure red and pure yellow, all these intermediate colors can be obtained.

All the color sensations of this region are therefore functions of a single variable (red or yellow) and can be represented on a straight line A.B., where A represents about 600 μμ and B 540 μμ.



Each point on the line represents a color sensation.

If any amount m_1 of light L_1 at A is mixed with an amount m_2 of light L_2 at B, then the resultant sensation is a light L_3 at C, such that

$$\frac{CA}{CB} = \frac{m_2}{m_1}.$$

Similarly, if m_3 of L_3 at C be mixed with m_4 of L_2 at B, the resultant sensation is a light L_4 at D, such that

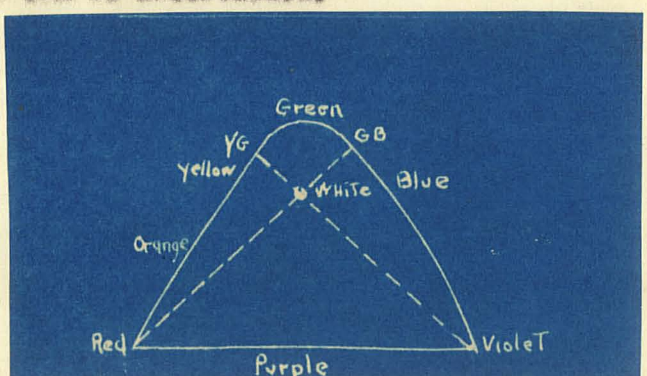
$$\frac{DC}{DB} = \frac{m_4}{m_3}.$$

Hence any combination of A and B can be matched by a single point taken between A and B. Thus the range from 600 μμ to 540 , must, like the purple range, be represented in the color diagram as a straight line.

Complications arise when the colors are chosen beyond these limits. If a yellow is mixed with a blue green, the resultant mixture, though resembling a pure intermediate color, does not match it perfectly. The match is made perfect by adding a certain proportion of white light to a pure spectral intermediate. In other words the mixture is paler and less saturated than the spectral match. As the distance between the mixing colors is increased the saturation becomes continuously less until finally at one distance two colors are obtained which, when mixed, yield a sensation of white, free from all traces of color sensation. These are called complementary colors.

See table on Page 18 of thesis.

Due to the fact that it is possible to pass continuously from blue to red. The graph representing this must form a closed curve in one plane. If three colors, neither of which can be obtained from a mixture of the other two, are represented by three points on a plane, then assigning to them values in terms of any unit, the situations and quantitative values of their mixtures can be ascertained.



The diagram will vary in form according to the source of light and according to the choice of units and fixed points. Figure is a diagram of a color table.

The position of the pure white sensation is obtained by dividing the line joining two complementary colors according to the relative amounts of these colors required to produce white when mixed together. The deviation of the curve from the straight line in the green yellow and beyond indicates the unsaturated nature of the mixtures. For example, mixtures of green and violet are less saturated than spectral cyan-blue. The curve, then, must deviate further from the white point than the straight line joining green and violet. From experimental results it is found that the curvature is sharpest in the green. The above color table includes every possible variety of color sensations.

Thus a law can be stated in general terms:

"The entire physiological valency of every conceivable light and light mixture can be comprehensively represented as the function of three variables."

STATEMENT OF THE YOUNG-HELMHOLTZ THEORY.

Based upon the above facts of color mixtures, it is found that every conceivable light or light mixture gives rise to a sensation which can be accurately matched by the sensation produced by a suitable mixture of only three lights (with a certain amount of white light added to the mixture). If we join three actual wave lengths R, G, and V on the color diagram by straight lines, we find

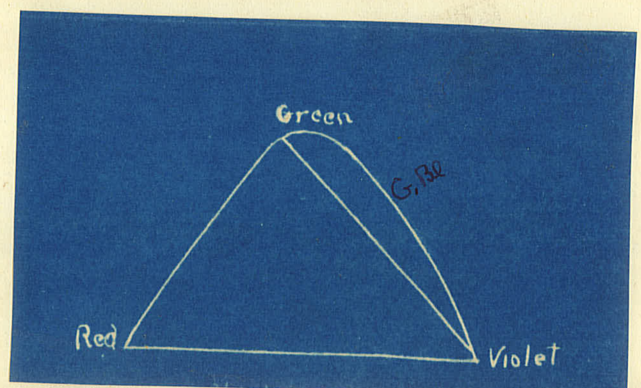


Fig 2

that part of the curve is outside the triangle thus obtained. This means that there are certain spectral colors which cannot be obtained in their full spectral saturation by the mixture of R, G, and V.

If a point is chosen on the curve outside the triangle, say G. Bl. , by experiment an equation of the following form can be obtained.

$$\alpha R + \beta G.\,Bl = \gamma G + \varepsilon V$$

thus the expression for G. Bl is

$$\beta G.\,Bl = \gamma G + \varepsilon V - \alpha R$$

which represents the unmixable color in terms of R, G, and V,. that unmixable color being the extra proportion of white which is found to underlie all color sensations.

In order to avoid negative quantities it is necessary to assume the existence of color sensations which lie outside the color diagram. It will be shown later on why pure unsaturated spectral colors can not be obtained.

The above assumption is minimised by describing a triangle around the diagram which will only just succeed in including every part of the diagram. Such is shown in the following figures.

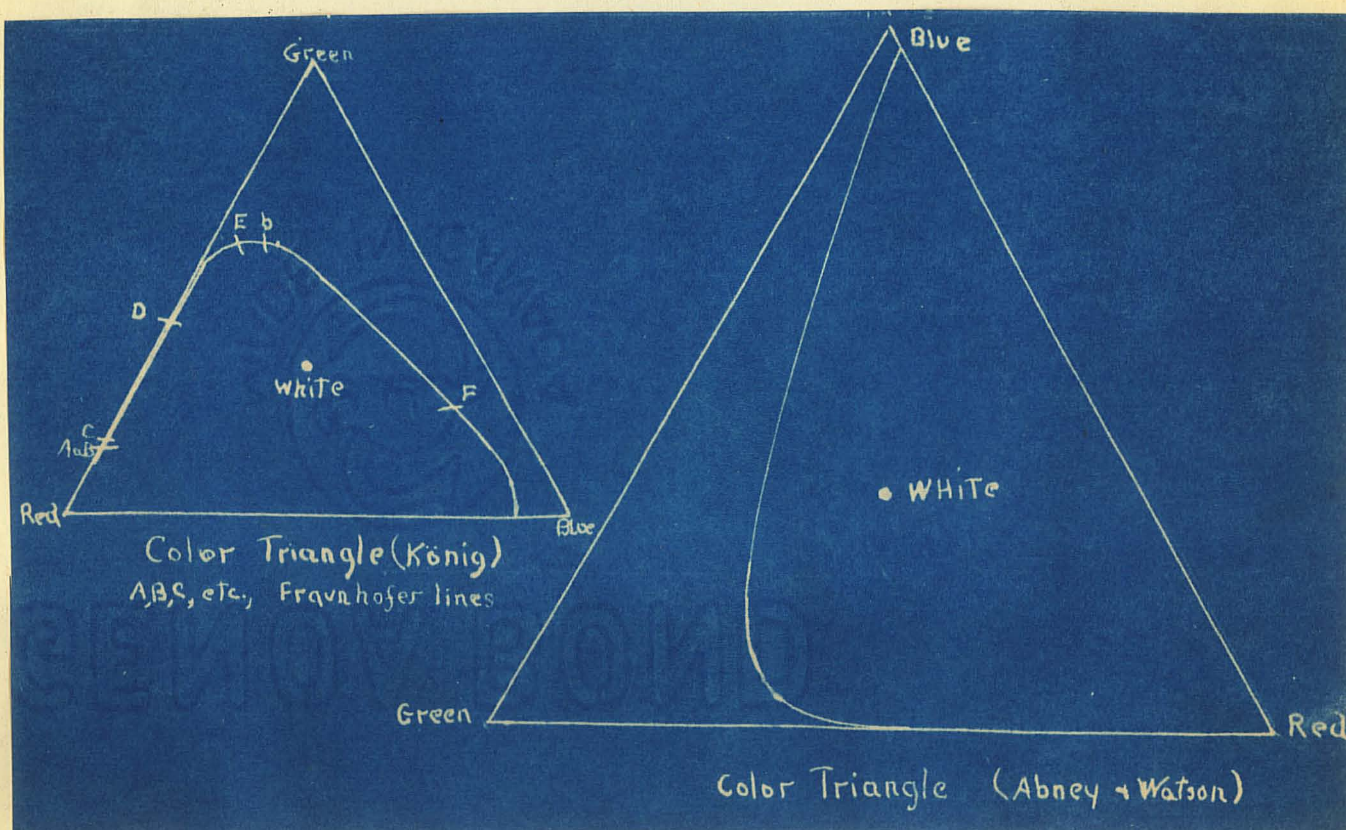


Fig 3

We can then obtain a general equation for any spectral color F,

$$F = xR + yG + zV$$

in terms of the three theoretical sensations R, G, and V, in which x, y, z, (the proportions of each light used) are all real positive quantities.

The objective quantities of light in this equation come into consideration here only as sensation stimuli (that is as different wave lengths) and as such have a physically measurable value. If a further assumption, viz., that the physiological processes (action on the retina) which accompany sensations, have a definite quantitative relationship to the physical stimuli (light waves), it can be said that x, y, and z are respectively the red, gree, and violet values of the light F in terms of the fundamental colors R, G, and V.

Suppose there is some method whereby it is possible to determine three measurable quantities a, b, c, representing three physiological processes, which taken together completely define the character of the visual sensations (three fundamental colors); it would be possible to find by observation the relationship between a, b, c, and the values x, y, z, of the incident light (those values which give rise to the sensations a, b, c).

a, b, c, would be represented as three functions of x, y, and z and conversely x, y, z, as three functions of a, b, and c.

That is:

$$a = f_1(x,y,z) \quad b = f_2(x,y,z) \quad c = f_3(x,y,z)$$

and

$$x = f_1'(a,b,c) \quad y = f_2'(a,b,c) \quad z = f_3'(a.b.c)$$

Since no two different groups of values for x, y, and z, give the same sensation (that is no two different mixtures of the three fundamental colors, can give the same sensation on the retina), or the same values of a, b, c;

therefore x, y, z can be expressed solely by a, b, c, (the incident light can be expressed in terms of the sensations perceived by the visual apparatus).

These values of the x, y, z functions of a, b, c (the $f_1' f_2' f_3'$) are therefore quantities which depend only on the character of the sensation, and moreover possess a certain individuality since each can be aroused, exist and again disappear in the nervous apparatus independent of the other two.

This independent existence is what is sought after in speaking of the elements or components of a sensation.

If we denote the function

$x = f_1'(a,b,c)$ by R

$y = f_2'(a,b,c)$ by G

$z = f_3'(a,b,c)$ by V

then these quantities R, G, V are to be denoted as the components of the color sensation and similarly any linear function of them (aR + bG + cV) may also be thus denoted.

Von Helmholtz states the Young theory from the mathematical elaboration of these assumptions:

"(1) In some part of the conducting nerve substance under the influence of colored light three different, independent and mutually unopposed elementary activities arise, called the elementary stimulations. Their amount is directly proportioned to the corresponding color values x, y, z, of the objective light; they correspond to the R, G, V of the above description."

"(2) All activities passing further towards the brain, as well as the sensations actually entering into consciousness under the given conditions of the reacting brain, are only actions of the three elementary stimulations R, G, V, and in amount are functions of a, b, c, of these elementary stimulations."

"(3) Either the elementary stimulations themselves or three mutually unopposed actions dependent upon them are conducted independently to the central organ."

These conclusions in a general and simpler way may be stated thus: R, G, V are any three points so situated that when joined the triangle thus constructed completely enclosed the color diagram of the given spectrum. In this manner positive values are ensured. From observations on color mixtures with the given spectrum it is possible to construct valency curves which represent the stimulation values of any spectral light for each of the three components R, G, V, of the resultant sensation. Thus:

$$F = xR + yG + zV$$

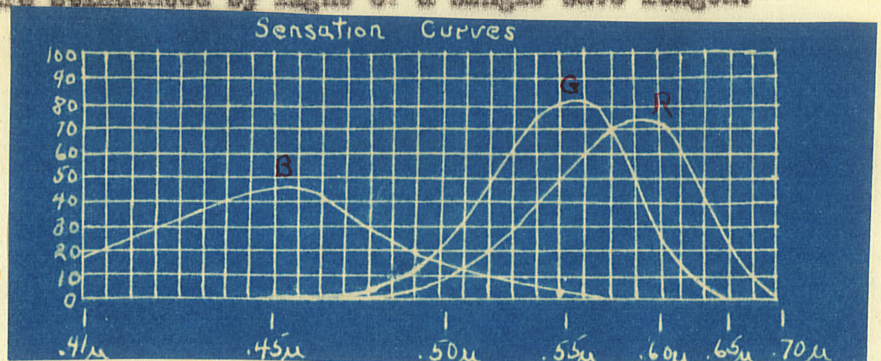
means that the light F is matched by a mixture of x parts of R light, y parts of G light, and z parts of V light, R, G, V being the physical stimuli in the mixture. If these physical stimuli act respectively upon the physiological counter parts or elements of sensation R, G, V, then xR, yG, zV clearly represent the strengths with which the light F acts upon the R, G, V elements.

The valency curves are, therefore, nothing more "than gauging curves" of the spectrum (See Fig. 3). Three colors are selected e.g. a red, a green and a blue. Each part of the spectrum is then matched by mixing different quantities of the three together. This process is called gauging the spectrum. But it has been shown that every gauging value belonging to one such group of curves must always be a linear function of the three gauging values belonging to any other group of curves. In any given spectrum, therefore, the R, G, V values must be some linear function of the three empirically observed gauging values (R,G,V). The three gauging curves, therefore, represent the relative values of the three sensations for each light throughout the given spectrum.

The above is a statement of the theory of Young and Helmholtz. The simplest concrete summary of it is, that there are three components in the eye which are counterparts of the physical stimuli. A component may represent a chemical, an electrical or some other process acting upon different substances, or nerve fibres and giving rise to nervous activity, but the general statement of the theory necessitates no such concrete conception.

Section B.

We have below the normal sensation curves of Abney and Watson (2). In the greater part of the spectrum the curves overlap, showing that all three sensations are stimulated by light of a single wave length.



That is, if we look at a color of wave length .573 it appears to our senses as a pure yellow with no hint of a red or green in it; examination of the above curves show, however, that this color is made up of equal parts of red and green sensations and a slight bit of blue sensation.

Although these curves are incomplete in the extreme red and violet ends of the spectrum, i.e. the red and green curves do not extend all through the blue sensation and the blue and green curves do not extend through the red sensation, which would indicate that the red sensation can be perceived in purity at one end of the spectrum and the blue sensation perceived in purity at the other end; such is not the case for Allen (3) in his luminosity curves has shown conclusively that all colors from the extreme red to the extreme violet ends of the spectrum affect all three sensations directly and reflexly.

Even though the curves of Abney and Watson are incomplete and show only the direct stimulation of the three sensations, sufficient quantitative evidence can be obtained from them to indicate the plausibility of

(2) Parsons - p. 244
(3) J.O.S. 1923, No. 7

the graphical method of showing the perception of colors.

On the Young - Helmholtz theory, the sensation produced by light of any color is the sum of the sensations arising from the stimulation of the three component mechanisms. This means that the ordinate of each of the above sensation curves for any particular wave length will give the proportion of each sensation present in that particular color. For example, taking the wave length .50μ found in the green region, we see that the heights of the ordinates of the three sensations are:

Red - 8 units

Green - 20 units

Blue - 15 units

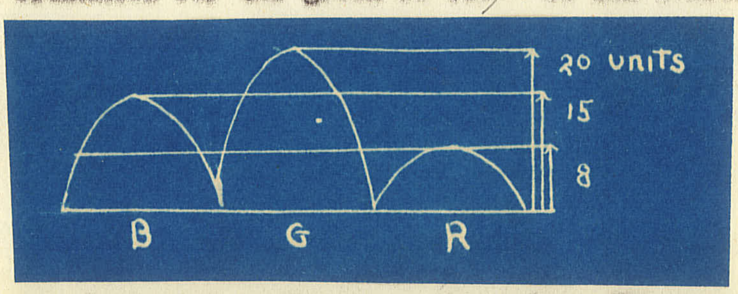
Similarly a yellow of wave length .573 has a sensation composition of:

Red - 68 units

Green - 68 units

Blue - 2 units

Using these quantities to indicate the height of each sensation above the base line, we can construct diagrams for each color. For example, using the heights of the ordinates for the green of .50μ we can construct the following diagram:



The following table shows the color, the wave length and the sensation composition for each particular color:

Color	λ	Sensation Red	Green	Blue
Red	.64 μ	31	4	-
Orange	.62	60	10	-
Yellow	.57	18	18	1
Green	.50	8	20	15
Blue	.45	2	2	43
Violet	.41	-	-	17

The dashes in the blue sensation of the Red and Orange colors, and in the Red and Green sensation of the Violet color indicate according to Abney's curves a lack of stimulation of these sensations; but an examination of curves 21 and 30 of Allen's (4) fatigue curves shows that the two sensations other than the fatiguing sensation are affected reflexly. Accordingly then, when any color is perceived all three sensations are partially stimulated.

This constitutes an important part of our perception of color.

It is generally recognized that all spectral colors are more or less unsaturated, that is, each color seems to be mixed with more or less white depending on its intensity. Parsons (5) states: "that great increase of intensity of a light not only alters its hue but also alters the saturation, till only white light is seen. It would seem, therefore, that luminosity is in some recondite sense an inherent "whiteness" in the color itself different in degree in different colors. Clearly we are at the outset face to face with a physiological fact of immense importance and much of the difficulty of color vision is concerned with this fact."

It seems then that this inherent "whiteness" is a part of the color itself and can not be in any way separated from it.

(4) J.O.S. Vol. VIII, No. 8, Aug. 24.
(5) Color Vision - p. 29.

Maxwell (6) found this to be the case and in the curves drawn from his color equations, part of the red and blue sensation curves are below the axis. These points represent negative quantities in the equations after the left hand members have been reduced to unity, and are due to the unsaturation of the color, caused by the inherent white light.

What is the origin of this inherent "whiteness"?

Allan (7) has shown that in addition to the usual direct action exercised by all colors upon the retina, every color also stimulates by reflex action the three fundamental sensations red, green and blue, particularly the sensation complementary to the impinging color, and also enhances the sensitiveness of their receptors. A consideration of the phenomena of the intrinsic or self light of the retina appears to show that the efferent nerve impulses in enhancing the receptors at the same time cause their stimulation with the resultant production of light. In consequence the brightness of the corresponding colors are increased to a greater or less degree according to the physical characteristics of the direct light. He has further shown (8) that the inevitable result of reflex stimulation of the three primary sensations is the production of white light in conjunction with every color affecting the eye. Should the two sensations other than the exciting sensation be stimulated equally the reflex white so formed, which underlies the color sensation, will be a pure white, but should the stimulation of the other two sensations be unequal the white may be tinted with yellow or blue. There is no way of predetermining what the appearance or color of the reflex light will be or whether it will be the same at all intensities. Peddie (9)

(6) Researches in Color Vision - Abney, p.227
(7) J.O.S. 1923, No. 7, p. 383
(8) J.O.S. Vol, 8, No. 2, 1924, p. 276
(9) Color Vision - p. 86

from mathematical reasoning concluded that the self light must be yellowish-white. This, according to the theory of reflex sensations, would imply that the red and green must be stimulated along with the blue in such a manner that either the red or the green be unequally stimulated compared to each other.

The conclusion arrived at is: that this white light, this self light, this inherent "whiteness", which underlies all color sensations is reflex in nature and must originate in the visual centers of the brain.

Now with this fact in mind, viz., when any ray of light falls on the retina it affects all three sensations, red, green and blue, to a greater or less extent depending on the intensity of the directly stimulating color, we shall now consider the color diagrams, which show the reflex effects on the stimulating color. While these diagrams, as previously mentioned, are constructed quantitatively, in part from Abney and Watson's sensation curves, the qualitative considerations of Allen's reflex sensation curves are also taken into account.

(1) RED. In the first diagram we have what the consciousness would distinguish as red, but what is actually red mixed with white and yellow. When red light falls upon the retina the sensory reflex excites the three fundamental sensations sufficiently to cause the perception of white of an intensity depending on the intensity of the original stimulation; the direct action of red affects the corresponding sensation predominantly resulting in the simultaneous perception of red. What appears finally to the consciousness, therefore, is the red color overlying a substratum of white.

If this white light was not formed by reflex action, at the instant of perception a color should appear at its full saturation. However, this is not the case, for, Bidwell (10) has shown that for an interval of

(10) Proc. Roy. Soc., 56, p. 132; 1894.

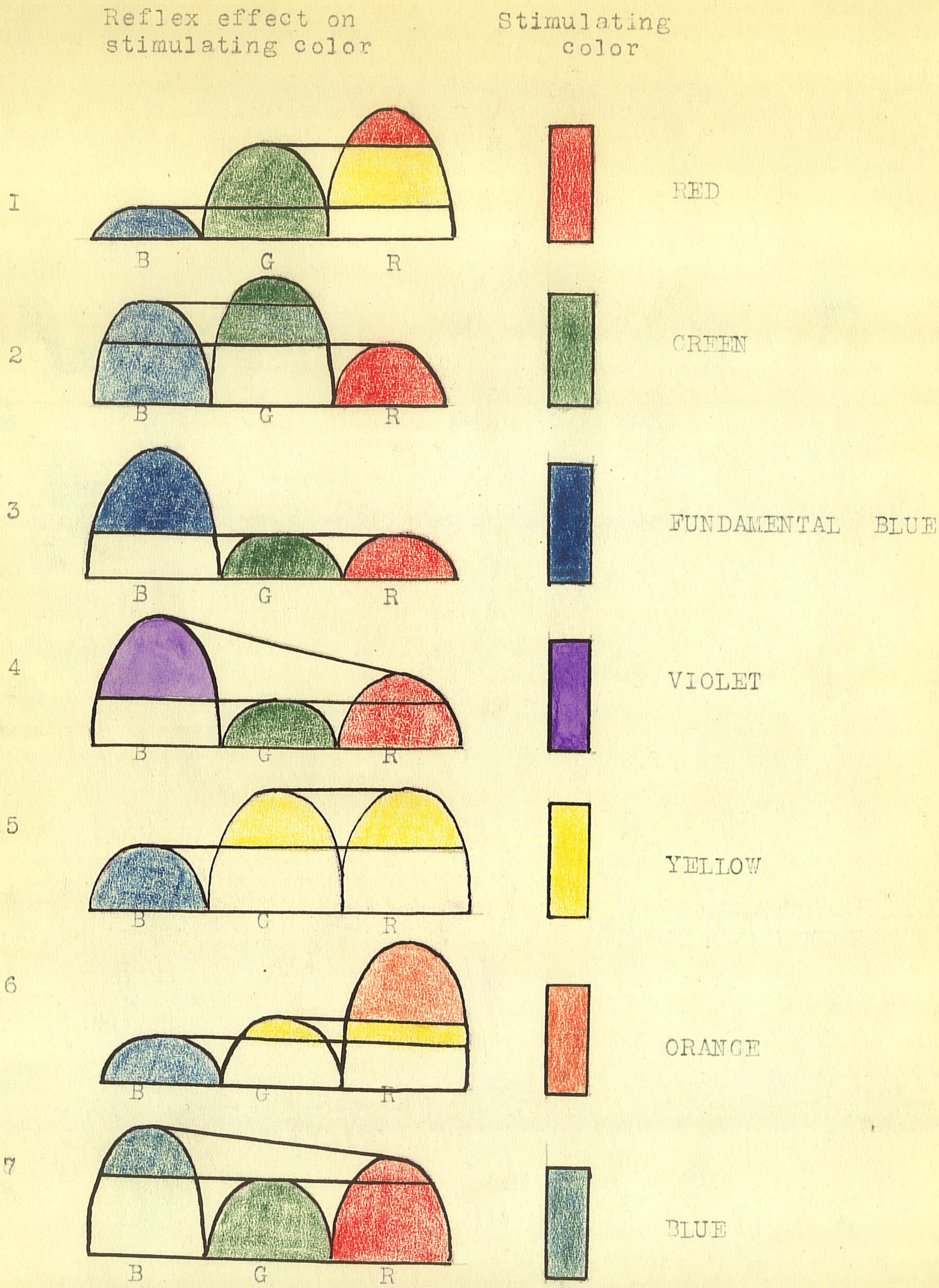


CHART SHOWING EFFECT OF REFLEX SENSATIONS ON THE DIRECTLY STIMULATED SENSATIONS.

one-sixtieth of a second after perception, all colors appear more saturated. This, then, must be the interval of time necessary for the formation of the efferent impulses which cause the reflex effects.

In this diagram a line drawn parallel to the base, through the peak of the least stimulated of the three sensations (in this case the blue), so as to cut theother sensations, represents the part of the three sensations which go to make up the white light underlying the color; this part is shown as white in the red sensation.

If the green sensation should be stimulated a slight bit more than the blue the extra stimulation would combine with more red to form yellow, so that the self light may be yellowish in appearance. A line drawn through the peak of the green curve parallel to the base represents the proportion of yellow present; this part is shown as yellow on the red sensation.

The red sensation, being the one directly stimulated, is much more intense than the other two; so the final result to the consciousness is indicated in the red curve, which shows a predominant red mixed with white and yellow.

(2) GREEN. In the second diagram we have the representation of a green color sensation. Considering this in the same manner as the first, we see that green light falling on the retina stimulates the green directly and the red and blue reflexly, with the result of partially stimulating the three sensations to give the white underlying the color. The line drawn through the least stimulated of the sensations gives the part of these sensations which form white indicated in the green sensation, as white.

In the diagram shown, the blue sensation is stimulated more than the red, which would result in the green having a blue tinge, if the red sensation were stimulated in excess, the green would be yellowish in appearance. Again the direct stimulation of the green sensation, being in excess of the other two sensations, causes the perception of an unsaturated green.

WHY GREEN HAS NO SPECTRAL COMPLEMENTARY.

It is impossible to mix green with any other spectral color so that the mixture will form white light; in other words green has no spectral complementary. The following table taken from Parsons (11) shows Helmholtz' estimates of the wave lengths of complementary colors.

Color		Complementary Color	
Red	656.2 $\mu\mu$	Green Blue	492.1 $\mu\mu$
Orange	607.7	Blue	489.7
Yellow	585.3	Blue	485.4
Yellow	573.9	Blue	482.1
Yellow	567.1	Indigo Blue	464.5
Yellow	564.4	Indigo Blue	461.8
Green Yellow	563.6	Violet	433. and beyond

It will immediately be observed from the above table that while each color when mixed with its complementary color gives white light, this white light is not formed from two single sensations, for in the combined make up of the color and its complementary there are always three sensations present. For example

Red plus Green Blue equals white

Yellow (Red plus Green) plus Blue equals white

etc.

It will be also observed that the green region from about 560 $\mu\mu$ to 492 $\mu\mu$ does not possess any spectral complementary. If the color selected

(11) Color Vision - p. 35

to match the green is chosen from the region beyond 560 $\mu\mu$ (Green Yellow) the blue necessary as the third sensation is lacking, and the other two sensations give combinations of yellow or orange. If, on the other hand, the color selected to mix with the green is chosen from the region beyond 492 $\mu\mu$ (Green Blue) the red sensation is lacking, so the resultant sensation is again compounded of only two colors. White light can only be produced from mixtures of three sensations; for a single sensation to form white with green would necessitate the presence of both red and blue, and as the only color of this mixture (purple) does not exist in the spectrum, green can have no spectral complementary.

(3) THE FUNDAMENTAL BLUE.

This sensation, which will be discussed shortly, would be similar in diagramatic representation to the other primary colors red and green.

(4) VIOLET: In the fourth diagram we have the color violet, which from the facts of color mixtures seems to be made up of blue and red. It is not possible to regard violet as a primary color, as we shall endeavor to show later on, even supposing it be one of the most saturated of the spectral colors. It may be that waves of the violet region, being half the wave length of those of the red region, are especially capable of arousing the red sensation directly, due to a color "undertone" as it were, causing the perception of a mixture of blue and red sensations which in the spectrum is violet, and with pigment mixtures, is purple.

The line drawn through all sensations in this diagram indicates the white part underlying the color; the sloping line between the red and the blue sensation indicates the dual nature of the violet sensation.

(5) YELLOW. Yellow is a compound color, that is, it is a color which has the red and the green sensations stimulated equally. Due to both the red and the green receptors stimulating the blue reflexly, the blue will be more aroused

than if a single stimulation acted on it. A greater proportion of the three sensations then should combine to give the white light underlying the color. This is actually the case as compound colors are much less saturated than the primary ones.

(6) ORANGE. Orange is considered to be made up of yellow and red, but yellow is made up of green red. An orange color then is one in which the direct red stimulation is considerably more intense than the direct green stimulation. All hues of orange are possible according to the excess of red stimulation over green stimulation

(7) THE ORDINARY BLUE OF THE SPECTRUM.

This blue sensation is not the true primary blue, but is excited by wave lengths much longer than those of the primary blue sensation. The reflex curves (12) show the ordinary blue to be made up of violet and green, the violet being formed as explained in diagram (4). Of necessity this blue must be very unsaturated in nature due to the intense stimulation of all three sensations by reflex action. The reflexes for the blue-violet region are by far the most powerful, so it is to be expected that more white light would underlie this color.

THE FUNDAMENTAL BLUE SENSATION.

The following table shows what different experimenters consider to be the fundamental colors:

	Red	Green	Blue
Helmholtz	Carmine red - not in spectrum	.56 μ to .54 μ	Ultramarine blue
Maxwell	.630 μ	.528 μ	.457 μ
König	Purple-red - just outside spectrum	.505 μ	.470 μ
Exner	.66 μ	.508 μ	.475 μ
Allen	Between end of spectrum and .66 μ	.570 μ to .470 μ	Violet between .420 μ and end

(12) J.O.S. 1923. No. 7

From a consideration of Allen's luminosity curves (13) it is shown that the fundamental or primary sensations seem to be red, green and violet, due to the fact that these three colors produce only one elevation (signifying fatigue) in the corresponding part of the spectrum, while the other colors, blue and yellow, produce two elevations (signifying fatigue of two color sensations, the elevations due to the yellow being the red and green regions, and the elevations due to the blue in the green and violet.

Allen concludes that the fundamental sensations are red, green and violet and that blue and yellow are compound colors.

Abney (14), on the other hand, states that the sensation violet is compounded from red and blue sensations. After a study of the sensation curves of Allen it is impossible to assume that the primary blue is the ordinary blue of the spectrum, yet from the facts of color mixtures there is considerable reason for assuming violet to be compound color made up of red and blue. We shall now consider by means of a triangle where the third primary sensation may be:

If Blue = (violet plus green) (1)

and Violet = (Red plus blue) (2)

then the blue sensation has a violet component and the violet sensation has a blue component.

Substituting the V sensation in (2) for the v component in (1)

$B = (R + b) + G$ (3)

and substituting the B sensation of (1) for the b component in (2)

$V = R + (V + G)$ (4)

It is evident then that the "b" component in (3) is the same as the "V" component

(13) J.O.S. Vol. VII, No. 8, Aug. 23, p. 607.
(14) Researches in Color Vision, p. 230

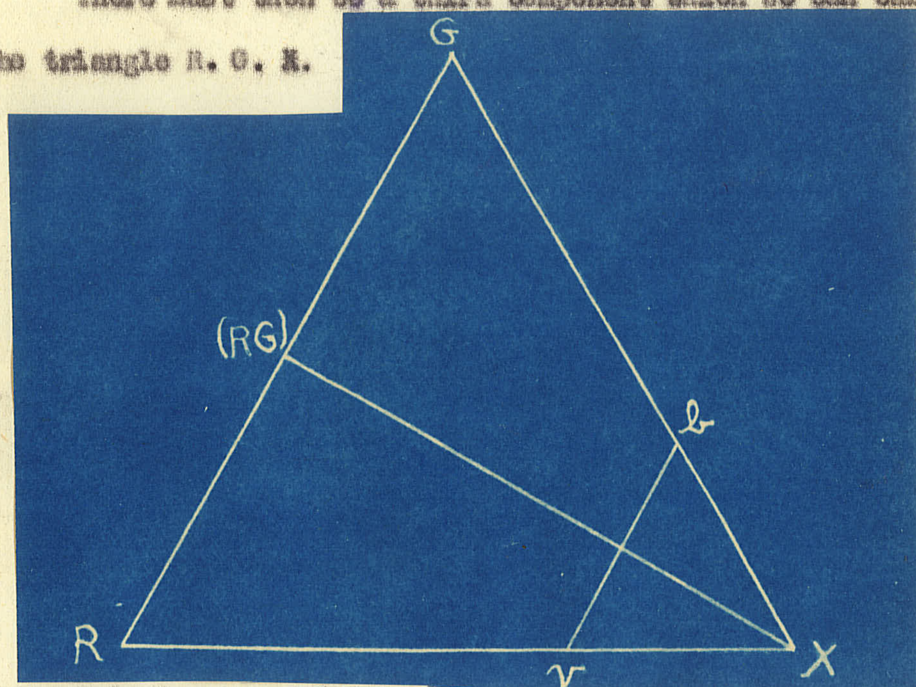
in (4). Otherwise the "b" on the right hand side of equation (3) would be similar to the "B" on the left hand side, and the "v" on the right hand side of (4) would be the same as the "V" on the left hand side, thus making

$$B = R + G$$

$$\text{and } V = R + G$$

which is a reduction to two color sensations instead of three.

There must then be a third component which we can call x. Consider the triangle R. G. X.



Along the line R to G we come to a point (R.G.) at which the red and the green sensations are capable of producing another sensation. Therefore all along the (RG)x, which is equidistant from side Gx, and side Rx, of the triangle, a sensation can be produced by a mixture of the Rx and Gxline of sensations. Perpendiculars dropped from line (RG)x to Gx give points on Gx which are blue in nature, and perpendiculars dropped to side Rx give points which are violet in nature. Thus when we reach the point x the peak of the triangle we reach a point where the violet and the blue sensations are the same. At this point the blue would be the fundamental blue; it would have no red in it such as found in the violet of the spectrum, nor would it have any green in it such as found in the ordinary blue of the spectrum. Such a point must be well out in the violet region.

If such is the case it is evident that a trichromat will be unable to distinguish the true blue sensation, due to the fact that waves, such as occur in this region also excite the red sensation and the resulting color perceived is violet.

Suppose, however, the red sensation was eliminated, then the colors beyond the ordinary blue, instead of becoming violet, would become a deeper blue, i.e. if the sensation of violet can only be formed when the red sensation is also present.

This condition is realized in the case of a red-green color blind subject. When waves of the violet region fall upon his retina, the red sensation being absent will not be stimulated resulting then in his perception of the real fundamental blue color. What is violet to be trichromat appears to him as blue.

Dr. Mary Collins (15) after a painstaking and minute examination of ten red-green blind individuals found that nine out of the ten had no sensation of violet and always called violet blue. She attaches no significance to the fact, but it forms remarkable evidence that the third primary sensation is a blue much deeper than the ordinary blue of the spectrum with its source somewhere in the violet region.

WHITE LIGHT FROM DAZZLING COLORS.

Abney (16) comparing the retina of the eye to a photographic plate, shows that if the image of a spectrum of dazzling brightness be developed, and the opacities of the different parts of the image be measured, it is found that the top of the curve (sensitivity curve of the silver salt used) is nearly flat for some distance on each side of the maximum point of sensitivity, instead of being a rounded point. This means that there is a certain region

(15) Color Blindness, Chap. VI.
(16) Researches in Color Vision, P. 219.

in which the waves of light are in tune with the molecules of the silver salt At moderate intensities, this maximum point is the only one affected to any extent, but at dazzling intensities all points immediately surmounting this one are affected, and maximum decomposition is obtained by rays not "in tune" with the atomic swing.

He concludes, the effect of a dazzling color on the retina should be similar. All three sensations are stimulated by, say, a green ray, the green sensation being in preponderance, If a dazzling green ray falls on the retina we have the green sensation at its maximum stimulation at once, and following quickly the red and the blue sensations reach their maximum stimulation, the effect is to produce the sensation white. The green would thus appear nearly white. From the sensation composition of an orange ray, which is red and green, we should find on using the same argument that the dazzle color of the orange would be a very bright yellow of a hue in which the two stimulated sensations are equal.

This phenomenon may be more easily explained when considered from the viewpoint of reflex visual sensations. Since each color directly, as well as reflexly, stimulates all three sensations, there must be a maximum intensity to which each can be directly excited. When the sensation directly concerned has reached its maximum further increase in intensity will be effective reflexly, only upon the remaining sensations until they are all at their maxima. This process can easily account for the disappearance of any particular color and its replacement by white.

Further, it is quite possible that as the intensity of thecolor is reduced, the reflexes diminish at a more rapid rate than the stimulating color, leaving an unbalanced residium of the color, at further reduction to lower intensities, the reflex effect again becomes equal in magniture to the color stimulus, resulting in the appearance of white or grey light instead of color.

REASON WHY GREEN IS THE LAST COLOR TO BE SEEN AT LOW INTENSITIES.

Langley (17) finds that the visual effect produced by any given constant amount of energy varies enormously according to the color of the light in question. It varies considerably between eyes which may ordinarily be called normal ones, but an average gives the following proportionate results for seven points in the spectrum where wave lengths correspond approximately with those of the ordinary color divisions, where unity is the amount of energy (about $\frac{1}{1000}$ erg) required to make us see light in the crimson of the spectrum, and where the preceding wave lengths given correspond approximately to the six colors: violet, blue, green, yellow, orange, red:-

Color	Violet	Blue	Green	Yellow	Orange	Red	Crimson
Wave length	.40 μ	.47	.53	.58	.60	.65	.75
Luminosity (Visual effect)	1600	62,000	100,000	28,000	14,000	1200	1

Thus we see that it takes only $\frac{1}{100,000}$ of the energy to produce the visual sensation in the green than it does in the red, the green, therefore, being the easiest color to visualize is the last to be seen at low intensities.

CONCLUSION

We have endeavoured to show how our color sensations are formed and how they have white light underlying them. Thus white light underlying all color perception has been widely recognized. In Hering's theory a separate visual process is assigned to the white black sensations. In Wundt's theory it is assumed that "two different stimulation processes are set in action by every retinal excitation, a chromatic and an achromatic. Both stimulations follow different laws with increasing stimulus intensities."

(17) Phil. Mag., Vol. 27, 1889, p.23

Mrs. Ladd-Franklin assumes that "in the earliest stages of its development the visual sense consisted of grey." Out of this achromatic sensation the color sensations developed by a process of molecular differentiation. The white light sensation is produced by the recombining of the same differentiated molecules.

McDougall provides an independent white process in addition to the three fundamental sensations red, green and blue.

But the assumption of the existence of a separate sensation for white is not necessary. With the aid of these diagrams we have demonstrated that only three sensations are essential to explain the formation, and the variation in hue, luminosity, and saturation of all colors and color mixtures.

PART II

A - SENSATION CURVES.

At the time the following curves were made, it was not known that the production of reflex visual effects depends on the intensity of the light used, with the result that the writer's curves do not show the same effect as W. A. Anderson's (1) which were obtained using the spectrum of an arc light to give the fatiguing colors. The writer used an acetylene flame to obtain the spectral colors, and found that this light was not intense enough to give reflex effects.

However, the curves indicate that the writer's type of vision belongs to the class of Anomalous Trichromats, with the abnormality in the red region between .64 μ and .70 μ. They also confirm one of Anderson's results, viz., that the red sensation is very difficult to fatigue, but is very susceptible to enhancement, indeed in practically all the curves the anomalous region is enhanced. It was also found that as the eye was fatigued with red, after a period of two minutes the red became yellow in appearance.

Anderson (2) found great difficulty in obtaining a normal curve, due to the gradual lowering of the normal as readings progressed. The writer found the opposite difficulty, a normal taken three months after the original normal was very much raised.

B - ANOMALOUS TRICHROMATISM.

The writer has at no time experienced any phenomena, apart from these experiments, to indicate that his vision is in any way abnormal.

It is well known that there are individuals who show no color

(1) J. O. S. Vol. 8, No. 6, June 1924
(2) Ibed, p. 735

deficiency whatever, but who, in matching spectral colors by two mixed colors, differ in their equation from that of the normal. For example, when making the equation

$$.670\mu + .535\mu = .589\mu$$

Some require more red and others more green than the normal. Those requiring more red are commonly called red anomalies, and those requiring more green, green anomalies. The explanation for anomalous Trichromatism afforded by the reflex theory is as follows: Since direct stimulation of the retina is always accompanied by a sensory reflex, then any abnormal development of the reflex stimulation must produce at least anomalous results in color vision. In general, therefore, anomalous Trichromatism is due to an abnormal ratio of the direct stimulation of the sensations to their reflex enhancement.

C - APPARATUS AND METHODS OF OBSERVATION.

The apparatus used and the method adopted was in most respects the same as that employed by Allen and Anderson, with the exception that the fatiguing light used was from an acetylene flame instead of an arc lamp.

The apparatus used to obtain the measurements was essentially the same as that originally devised by E. L. Nichols. (1) The source of light was an acetylene flame for which the gas was supplied at a constant pressure. The light was focused upon the slit of the collimator of a Hilger spectrometer, fitted with four prisms equivalent to three of sixty degrees each; this gave a spectrum of considerable dispersion, narrow strips of which could be isolated in a shutter eye piece. Between the acetylene flame and the condensing lens an aluminium disk with two opposite open sectors of ninety degrees each was rotated. The speed of rotation, which was regulated by

(1) E. L. Nichols, A.M. Jour Sci. 28, 1884.

means of a brake, was electrically recorded upon a chronograph. The gas flame was enclosed on all sides, except the top, in a wooden box with a small glass window which transmitted the light to the spectrometer. This box served two purposes, first, in preventing the air currents, produced by the rotating disk, from affecting the flame, and second, in shielding the light from the observer's eyes. The spectrometer was properly screened from all extraneous light, and a shield closely fitting about the eye was attached to the eyepiece, thus enabling all measurements to be made under exactly the same conditions.

The spectrum used for fatiguing the eye was obtained from an acetylene flame, using one collimator of an Allen Tricolor mixing spectrometer. A narrow but quite long rectangular patch of the spectrum was isolated by the shutter eyepiece.

While fatiguing the right eye, the unused eye was always directed at a neutral gray surface about four inches away.

All the apparatus was mounted in a room well illuminated with daylight.

The rotating sectored desk produced a flickering sensation in the isolated patch of the spectrum, due to the rapid succession of equal intervals of color and darkness. After adjusting the speed of the motor until the flicker was just imperceptible, the chronograph was started, and while the record was being made, which required about half a minute, the speed of the disk was adjusted to keep the flicker just on the point of appearing and disappearing. At least two independent records were made for each point.

The following was the procedure adopted in making measurements for a normal curve. The spectrometer was set so that the shutter eyepiece isolated a narrow rectangular patch of the spectrum, the mean wave length of which was known. The spectral color was observed by the right eye while the speed of the disk was regulated to give the critical frequency. The eye was always fixated on a dust speck on the right hand side of the slit. The eye was rested from four to six minutes between each reading. In this way observations were made at fifteen different points in the spectrum.

The persisting curves obtained by plotting wave lengths as abscissae and the persistence of vision as ordinates, show that the duration of these light impulses varies as some inverse function of the luminosity of the color observed. It was discovered by Ferry (3) and subsequently by Porter (4) that the duration of the sensation of undiminished brightness of a flash of light, at the critical frequency of flicker, depends only on the luminosity of the light and in no way on the wave length. The Ferry - Porter law is represented by the equation

$$D = \frac{1}{K \log L + K_1}$$

where D is the persistence of vision

L is luminosity.

K and K_1 two constants.

According to this law then a lowering of the persistency curve may be interpreted as an increase and and elevation as a decrease in the luminosity of the spectrum as perceived by the eye.

In obtaining the fatigue curves, the procedure was similar to that of the normal curves, with the exception that the right eye was first fatigued for two minutes with the given spectral color. Care was taken to prevent it wandering. The interval elapsing between the removal of the eye and the commencement of the chronographic record was about 30 seconds, while the time taken to make the record was another 30 seconds. The readings for an

(3) Am. Jour. Sci. 44, 1892
(4) Proc. Roy. Soc. 63, 1898; 70; 1902

entire curve were taken at one session of two to two and a half hours.

By fatiguing the left eye with the various colors, curves were also obtained using the right eye to make the measurements. Due to the intensity of the light from the acetylene flame being too low, these curves do not show the reflex effects similar to Anderson's.

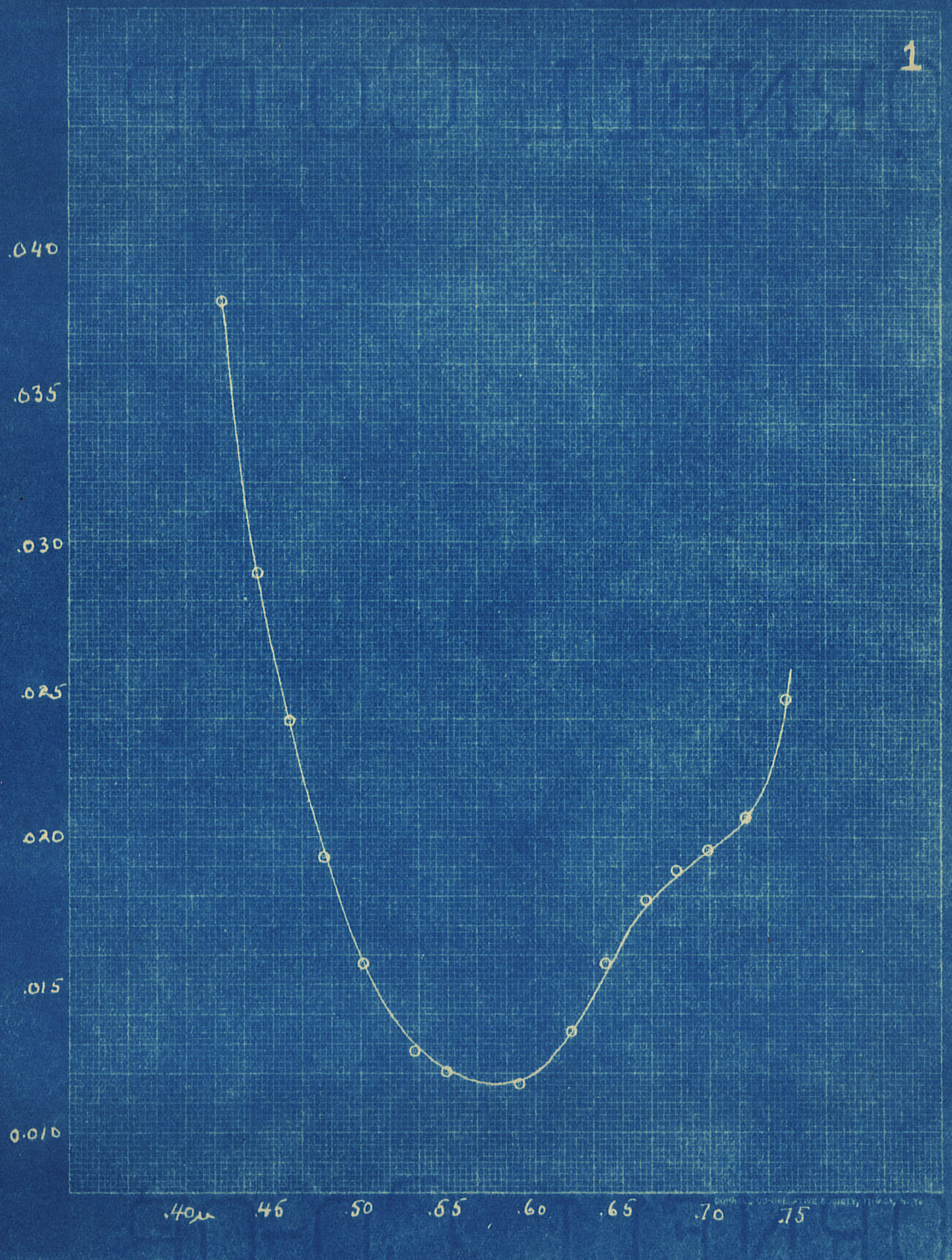
The following curves were taken over a period lasting about three months. The data table for each curve is numbered the same as the curve.

Normal Curves. / Fatigue Curves.

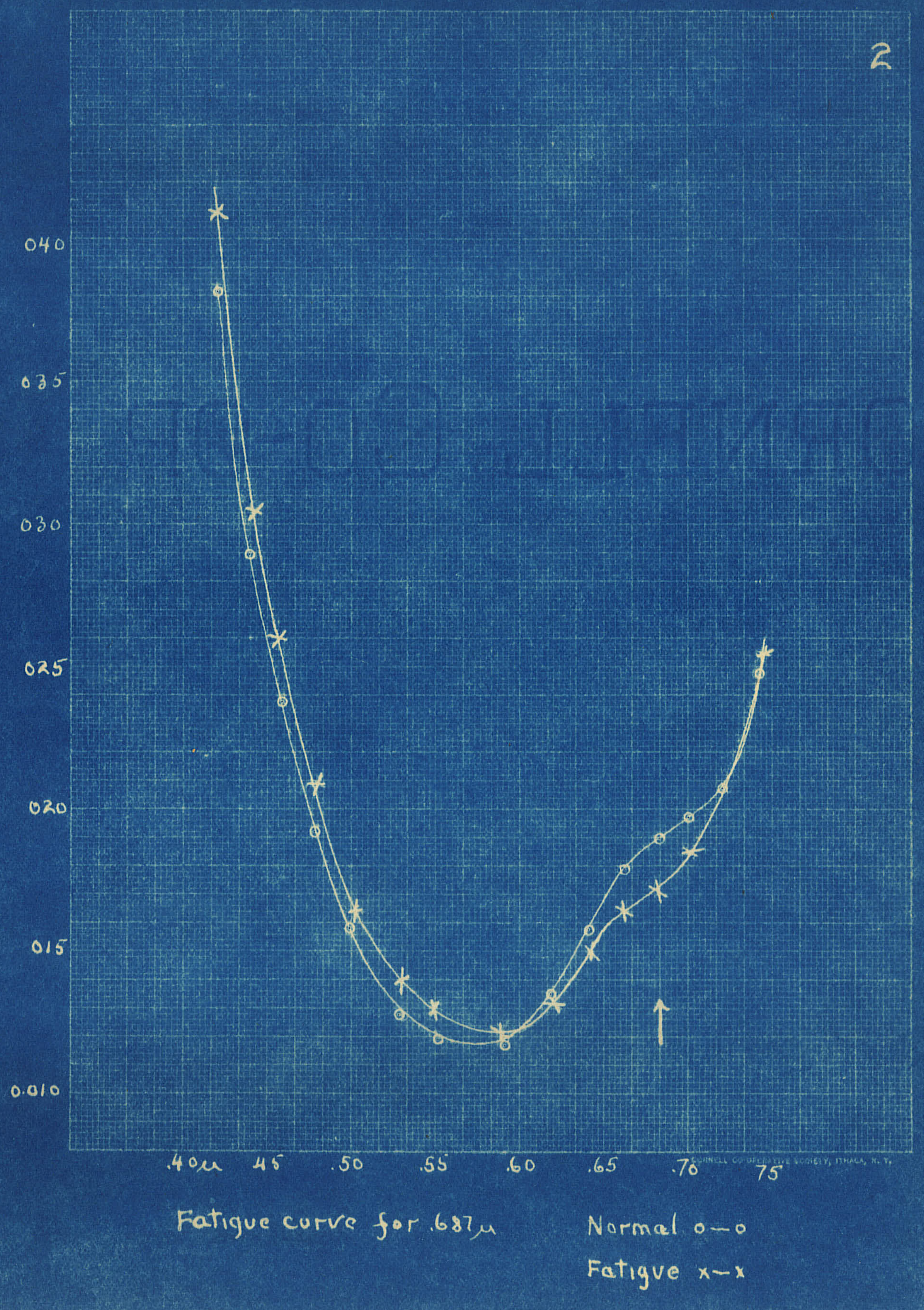
λ	No. I	No. 22	.687μ No. 2	.660μ No. 4	.589μ No. 6	.570μ No. 8	.505μ No. 15
	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.
.74μ	.0248	.0269	.0251	.0246	.0266	.0269	.0267
.72	.0206	.0242	.0214	.0215	.0226	.0224	.0209
.70	.0197	.0204	.0184	.0194	.0197	.0203	.0180
.68	.0190	.0175	.0170	.0177	.0180	.0179	.0160
.66	.0180	.0167	.0166	.0170	.0175	.0175	.0154
.64	.0158	.0162	.0156	.0153	.0166	.0165	.0140
.62	.0136	.0149	.0130	.0138	.0138	.0146	.0131
.59	.0118	.0128	.0122	.0131	.0122	.0127	.0117
.55	.0123	.0135	.0132	.0134	.0123	.0127	.0121
.53	.0127	.0143	.0137	.0142	.0137	.0135	.0130
.50	.0159	.0176	.0164	.0171	.0168	.0187	.0156
.48	.0194	.0212	.0170	.0218	.0205	.0205	.0190
.46	.0250	.0250	.0260	.0252	.0256	.0277	.0222
.44	.0290	.0315	.0306	.0310	.0331	.0306	.0273
.42	.0389	.0359	.0410	.0340	.0377	.0415	.0340

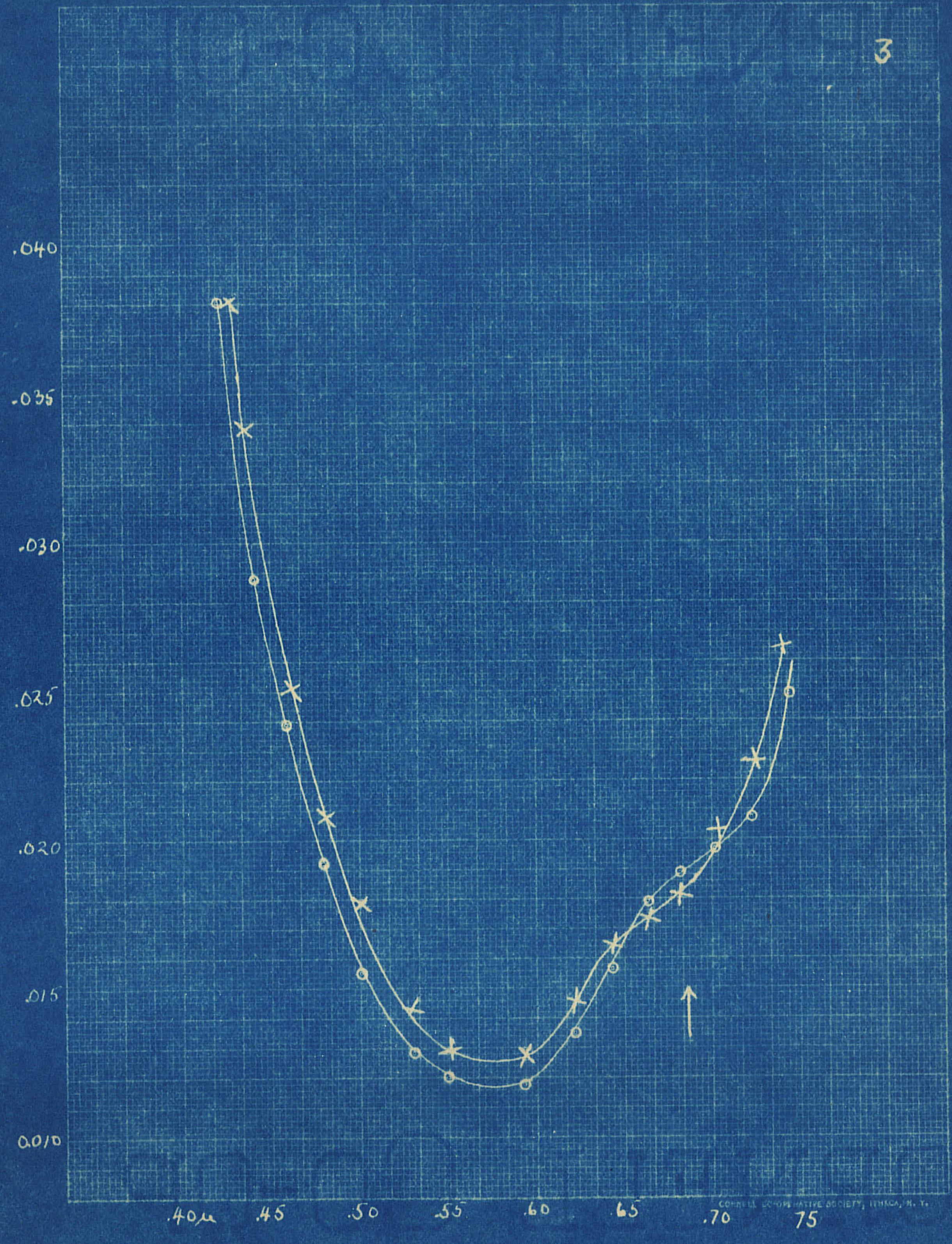
Fatigue Curves.

	.535μ No. 10	.520μ No. 12	.505μ No. 14	.450μ No. 16	.425μ No. 18	.410μ No. 20
	Sec.	Sec.	Sec.	Sec.	Sec.	Sec.
.74μ	.0266	.0279	.0269	.0269	.0271	.0281
.72	.0234	.0231	.0236	.0223	.0208	.0216
.70	.0217	.0192	.0204	.0186	.0190	.0200
.68	.0196	.0182	.0183	.0173	.0179	.0185
.66	.0177	.0176	.0178	.0161	.0175	.0171
.64	.0166	.0162	.0164	.0152	.0154	.0162
.62	.0151	.0141	.0145	.0140	.0142	.0143
.59	.0130	.0121	.0126	.0122	.0125	.0126
.55	.0130	.0124	.0128	.0121	.0127	.0125
.53	.0137	.0133	.0136	.0127	.0137	.0136
.50	.0175	.0166	.0161	.0167	.0170	.0172
.48	.0204	.0198	.0211	.0193	.0210	.0198
.46	.0266	.0256	.0252	.0246	.0256	.0246
.44	.0313	.0319	.0312	.0302	.0305	.0291
.42	.0397	.0403	.0381	.0362	.0400	.0378

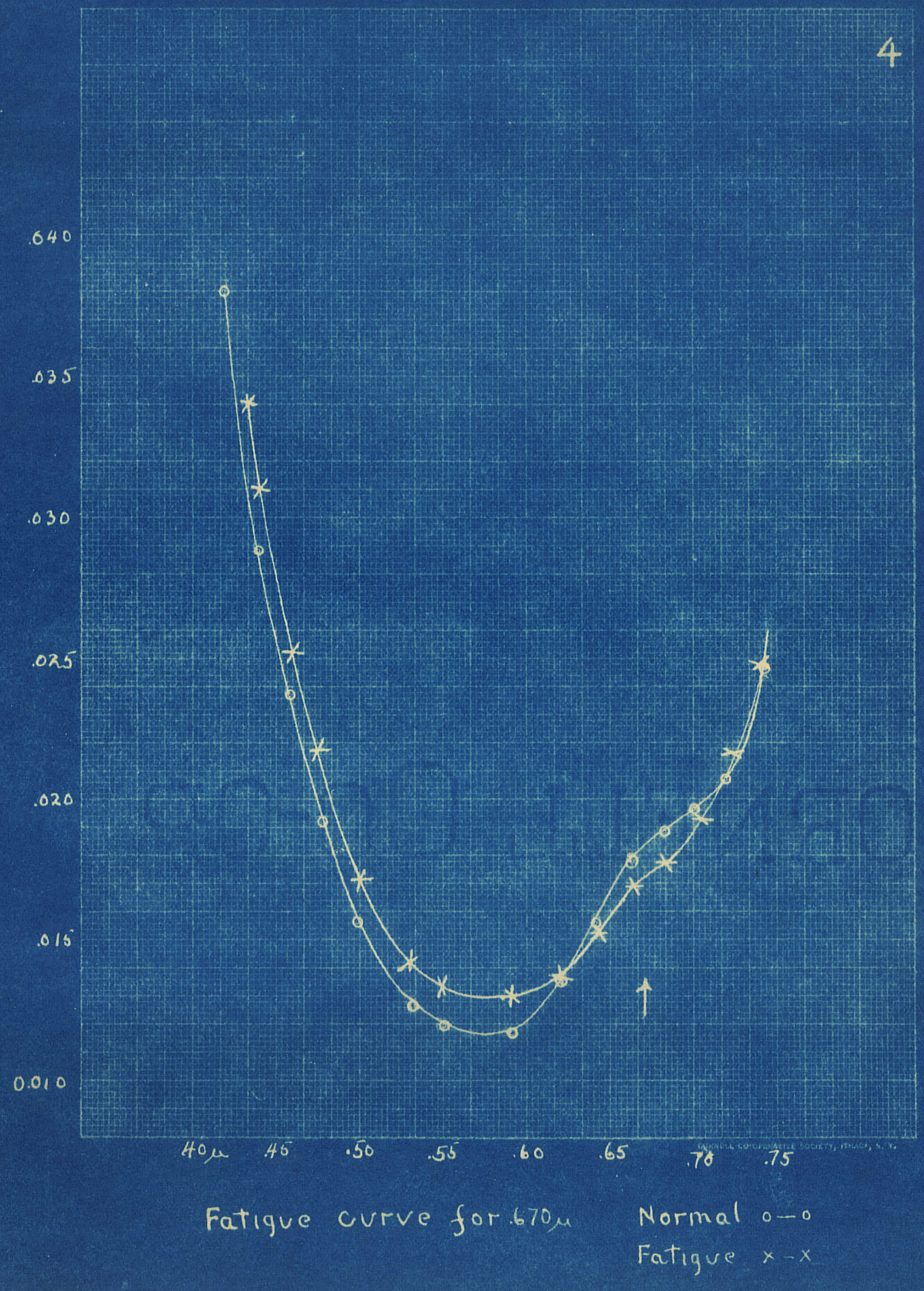


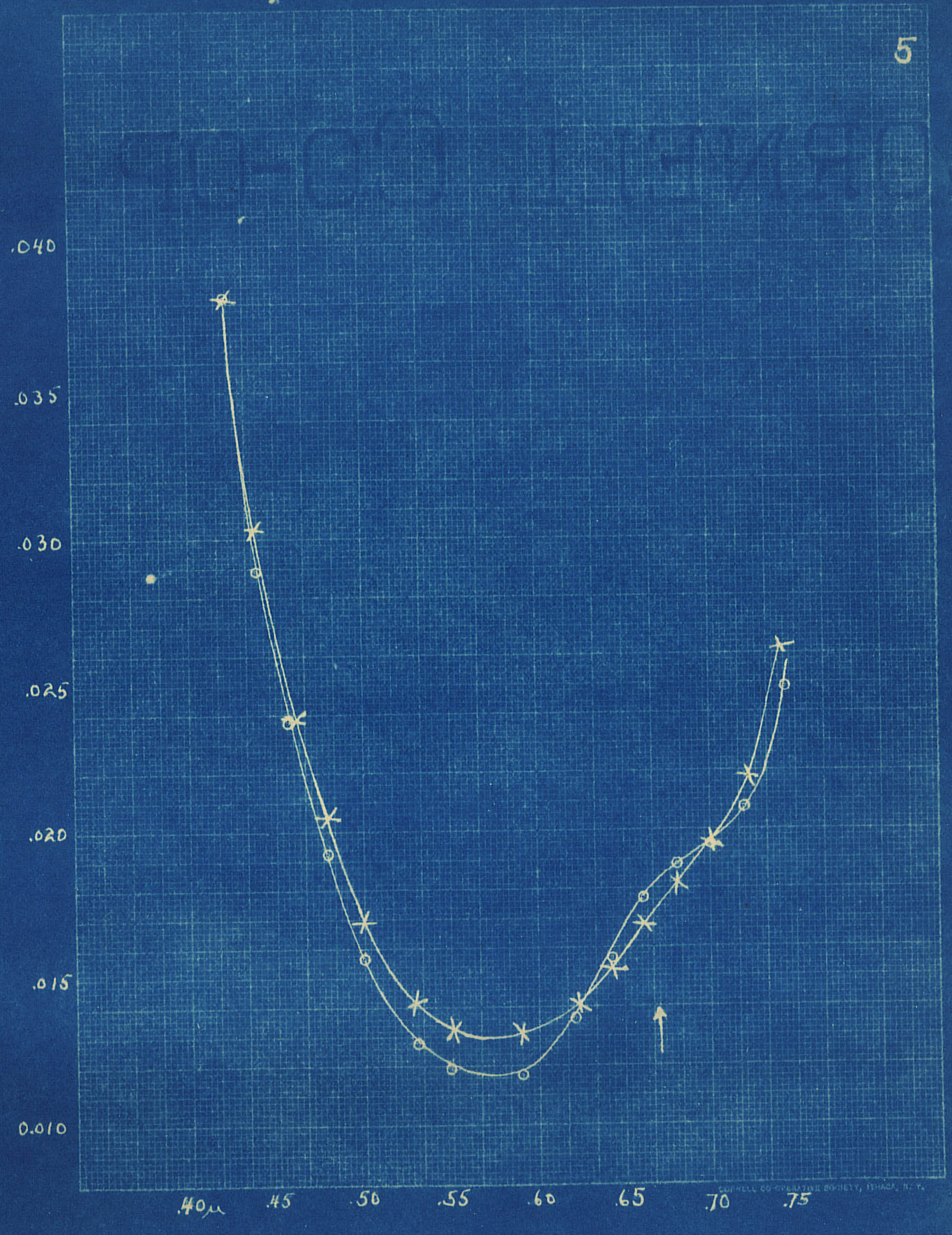
Normal Curve


2
040
035
030
025
020
015
0.010
.40μ
45
.50
.55
.60
.65
.70
75
CORNELL CO-OPERATIVE SOCIETY, ITHACA, N. Y.
Fatigue curve for .687μ
Normal o—o
Fatigue x—x

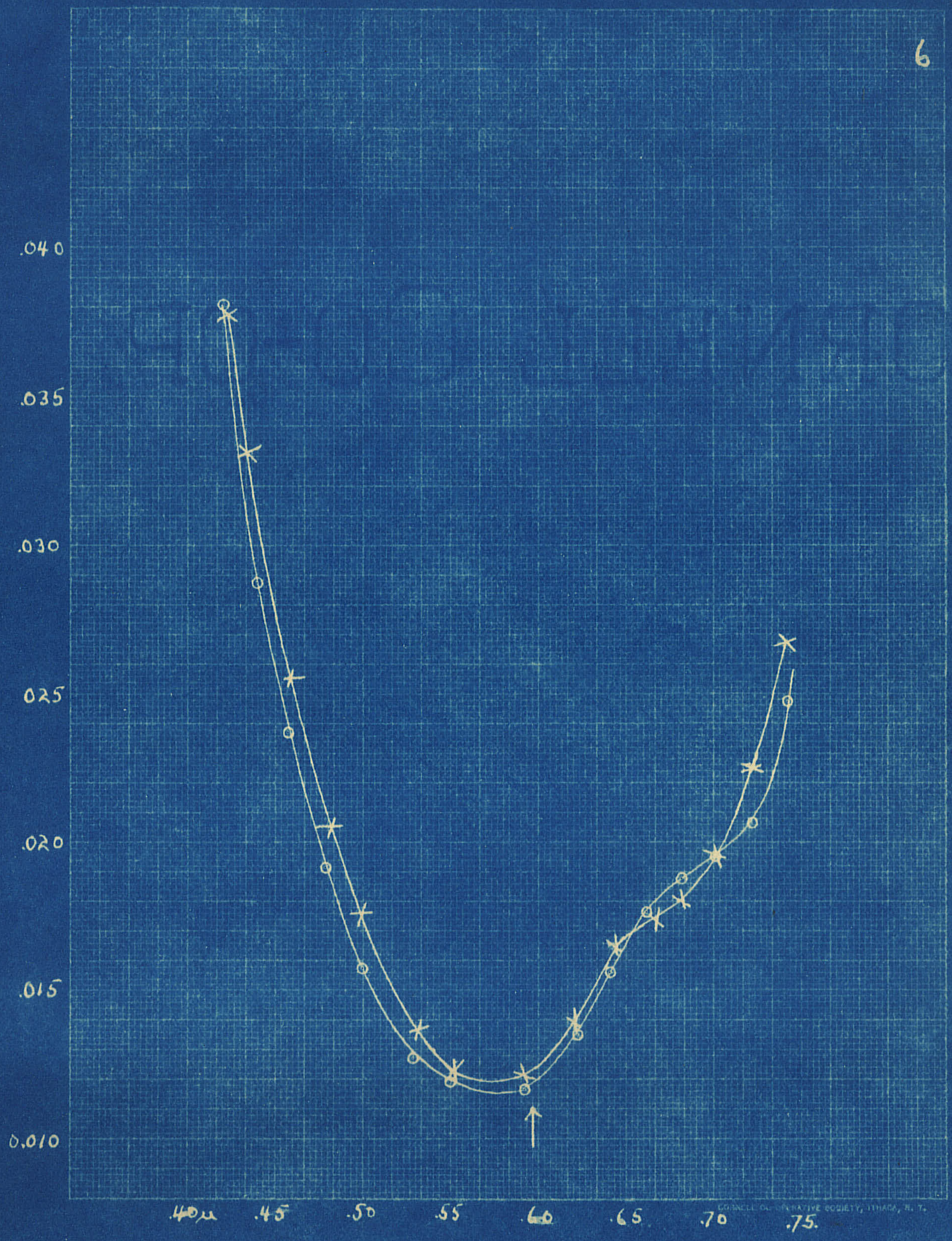


Reflex curve for .687μ   Normal o—o
Reflex x—x


4
.040
.035
.030
.025
.020
.015
0.010
40μ
.45
.50
.55
.60
.65
.70
.75
Fatigue curve for .670μ
Normal o—o
Fatigue x—x

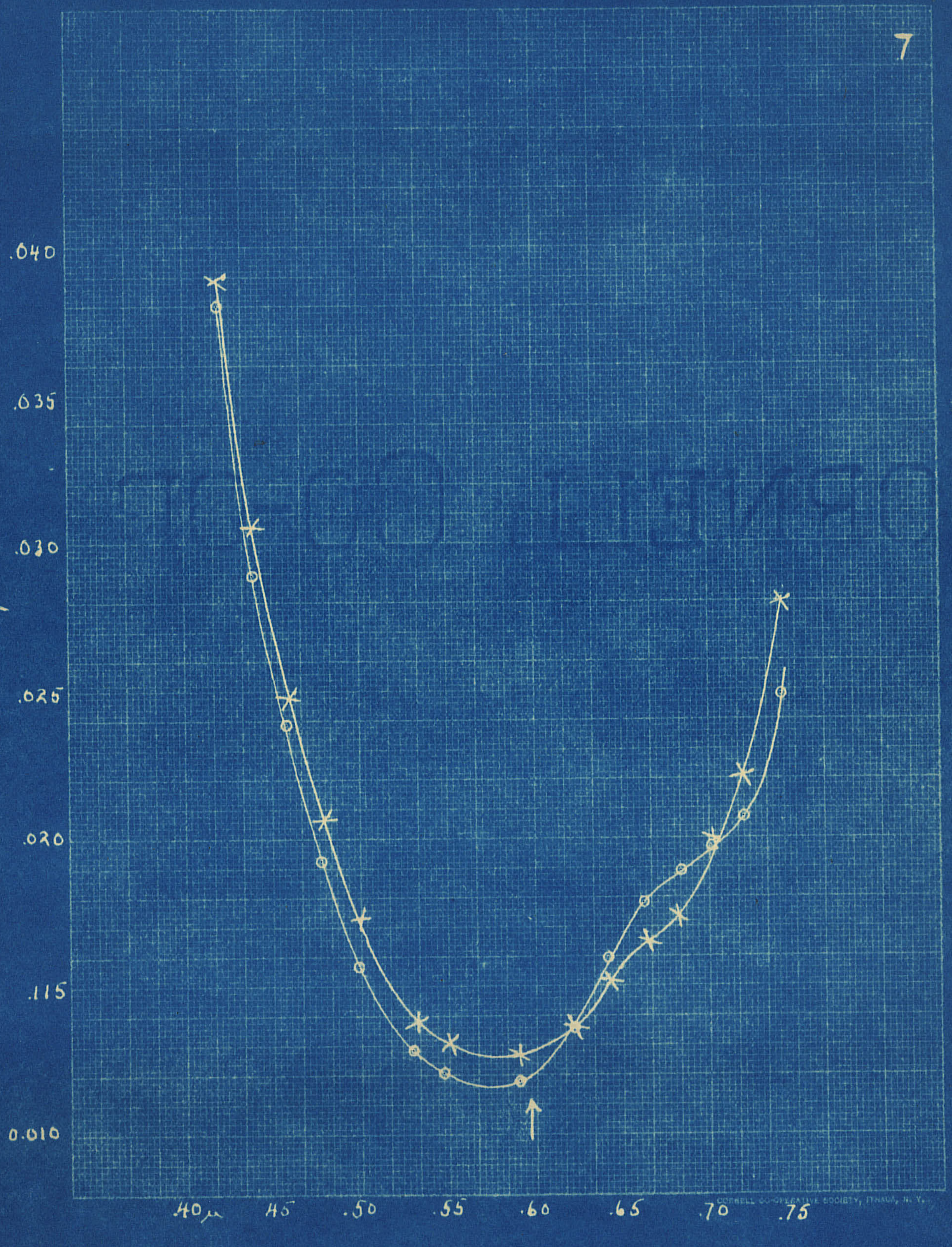


Reflex curve for .670μ   Normal o—o
Reflex x—x



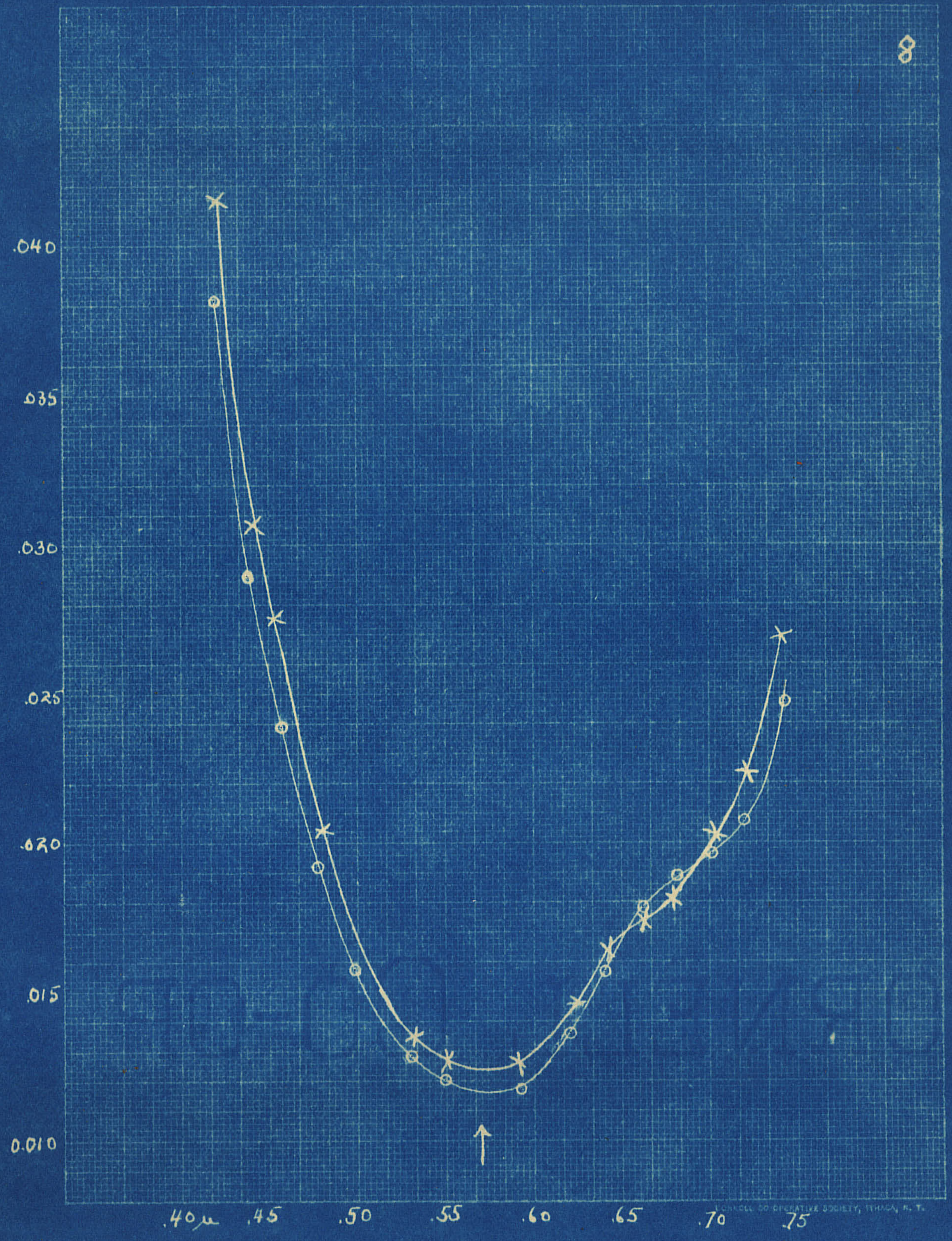
Fatigue curve for .589μ   Normal o—o

Fatigue x–x



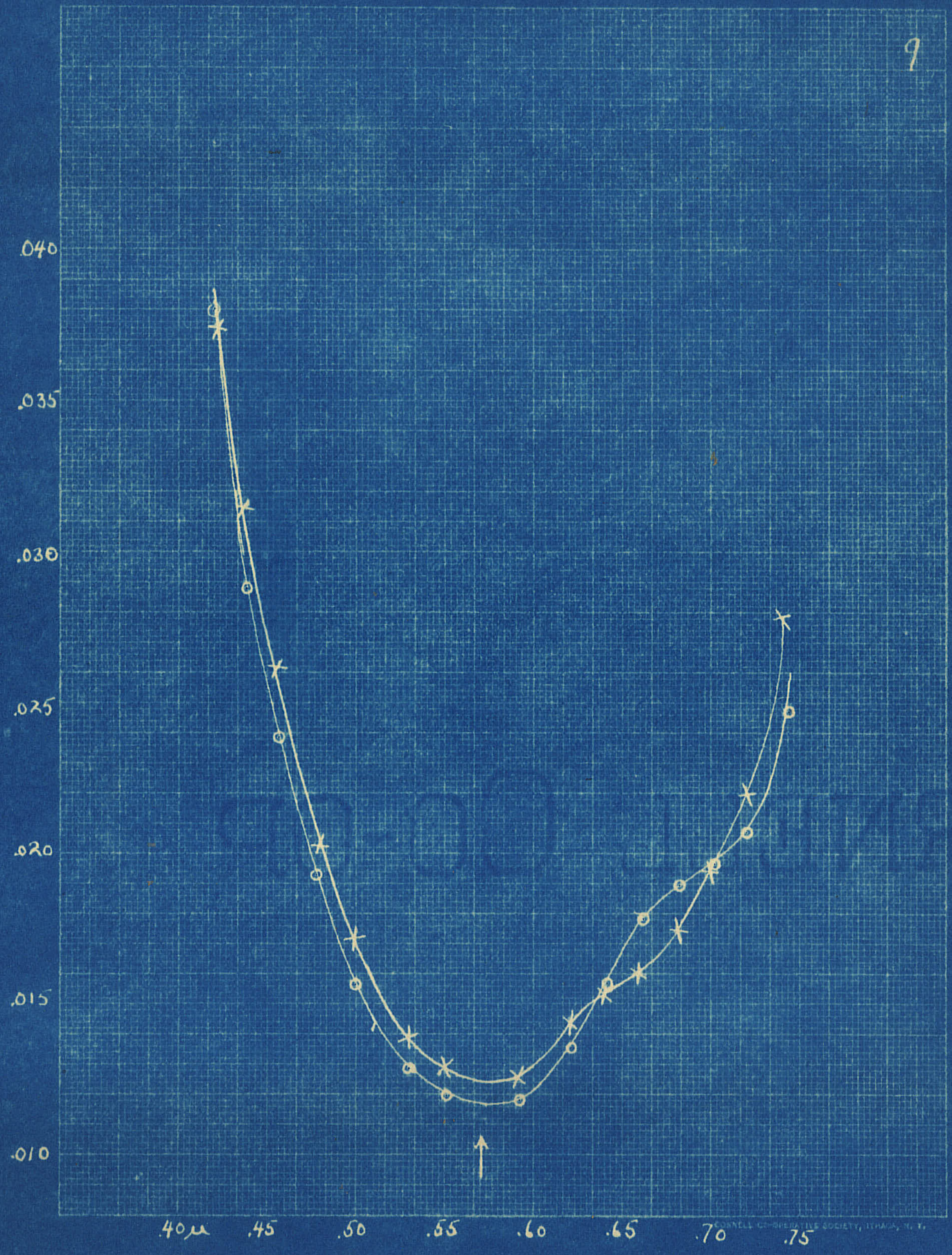
Reflex curve for .589μ Normal o—o

Reflex x—x



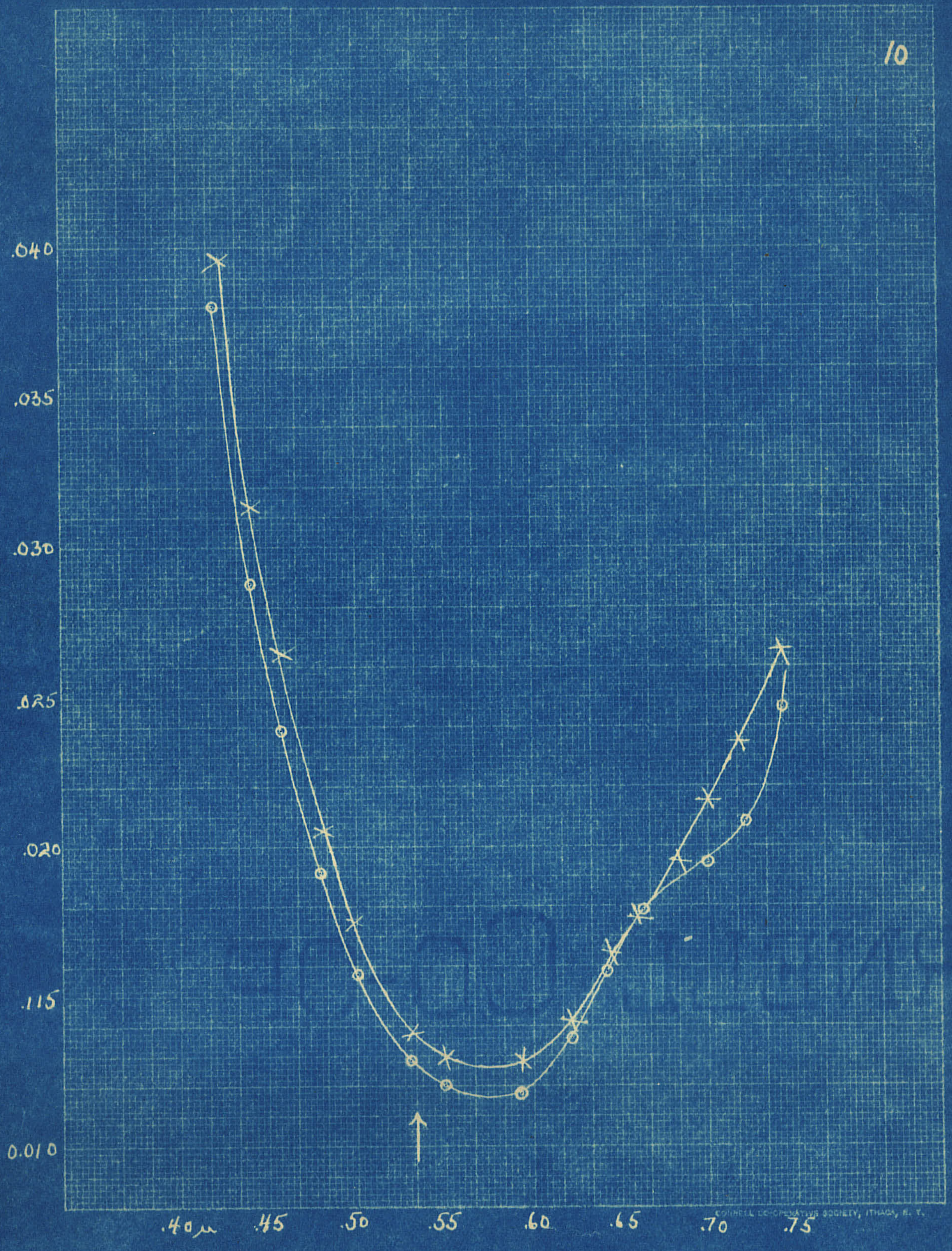
Fatigue curve for .570μ

Normal o—o
Fatigue x—x



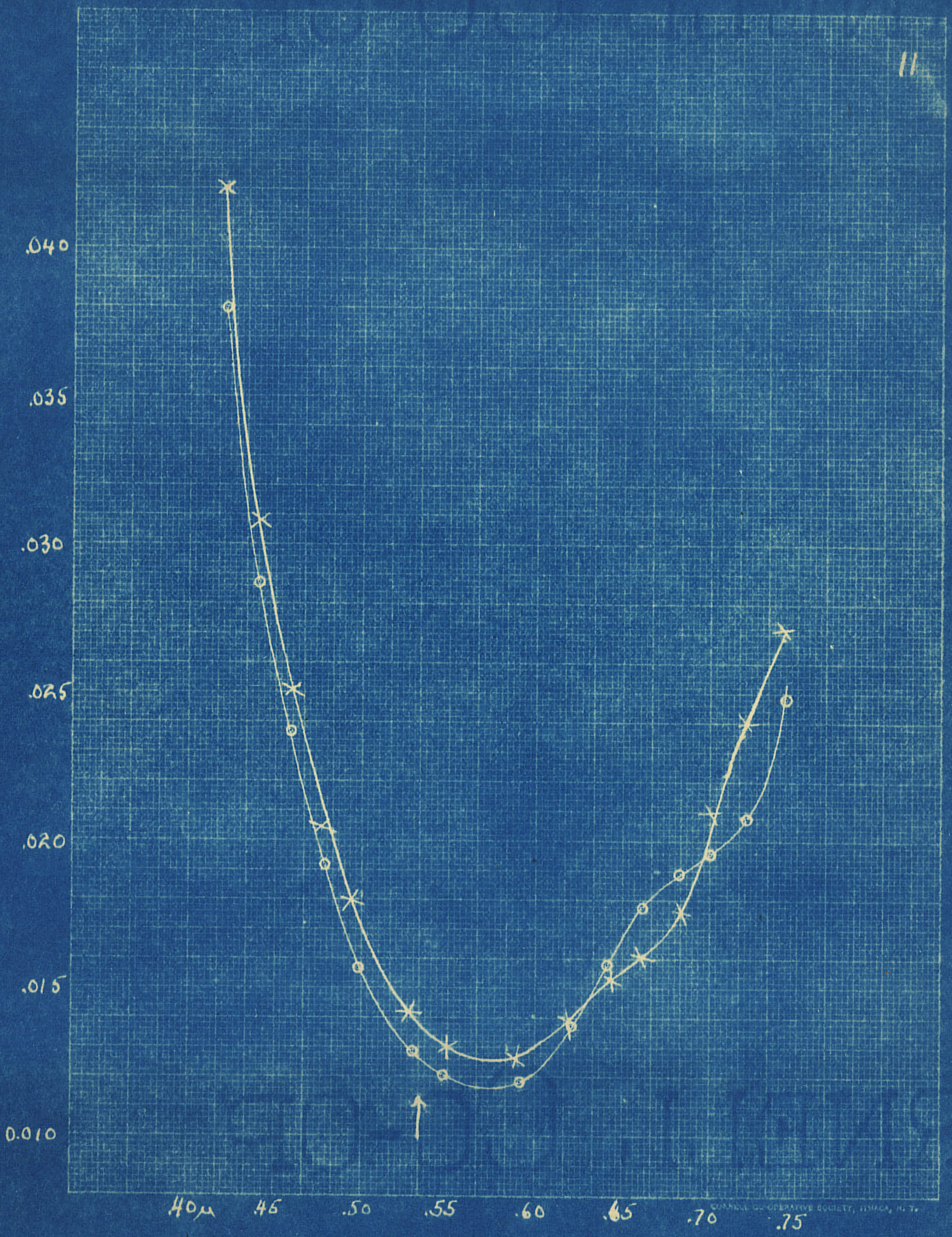
Reflex curve for .570 μ   Normal o — o

Reflex x — x



Fatigue curve for .535μ   Normal o—o

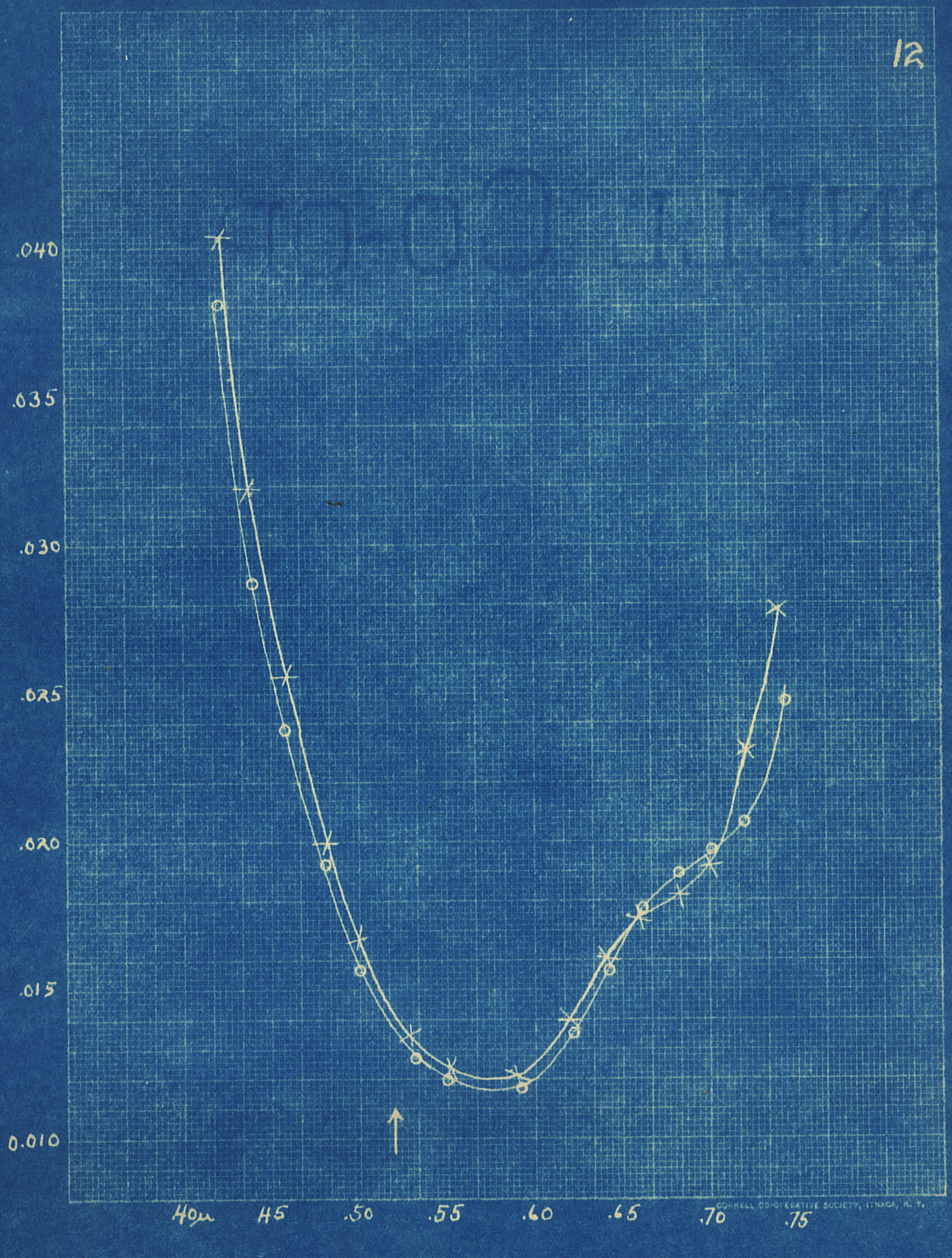
Fatigue x—x



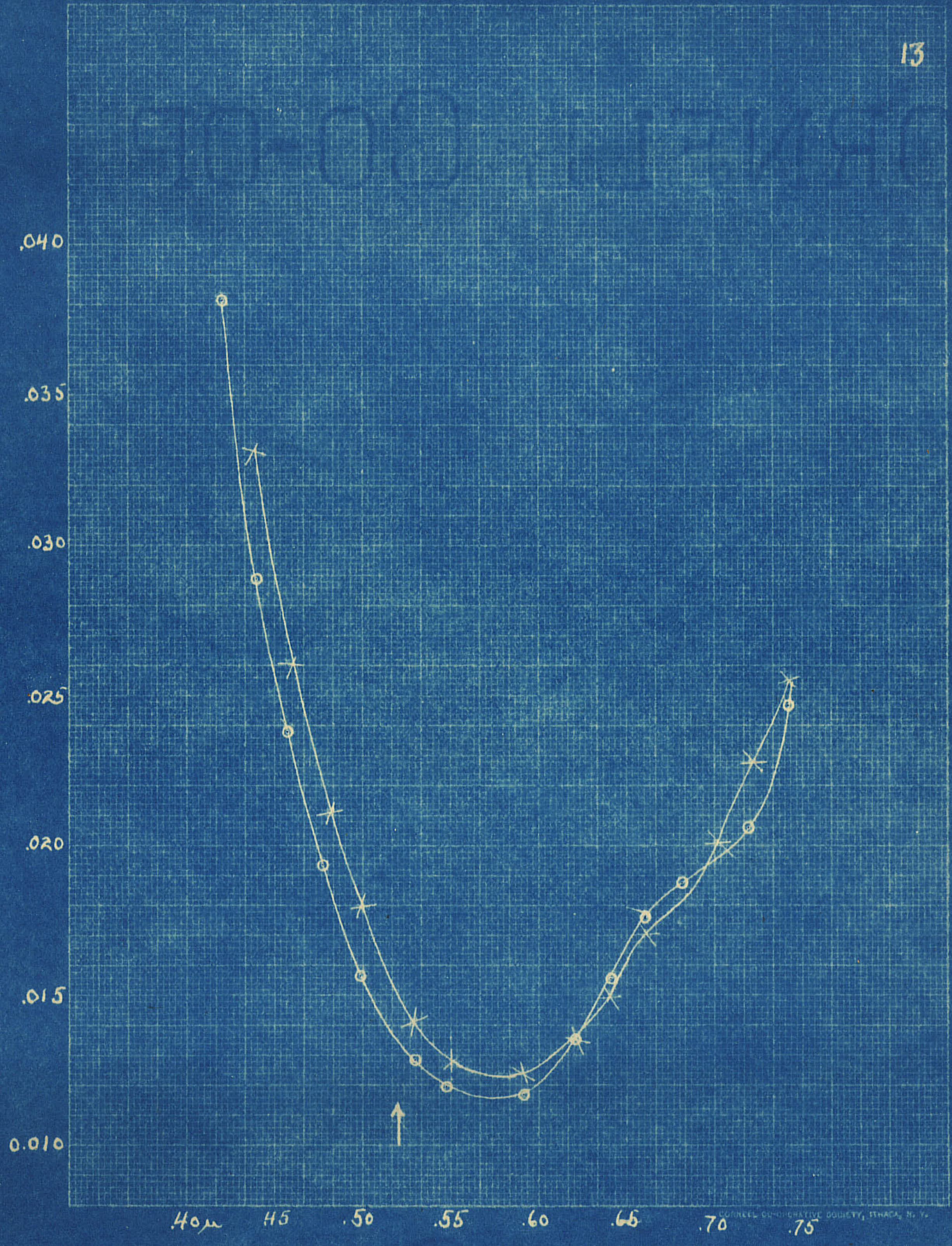
Reflex Curve for .535μ

Normal o—o

Reflex x—x

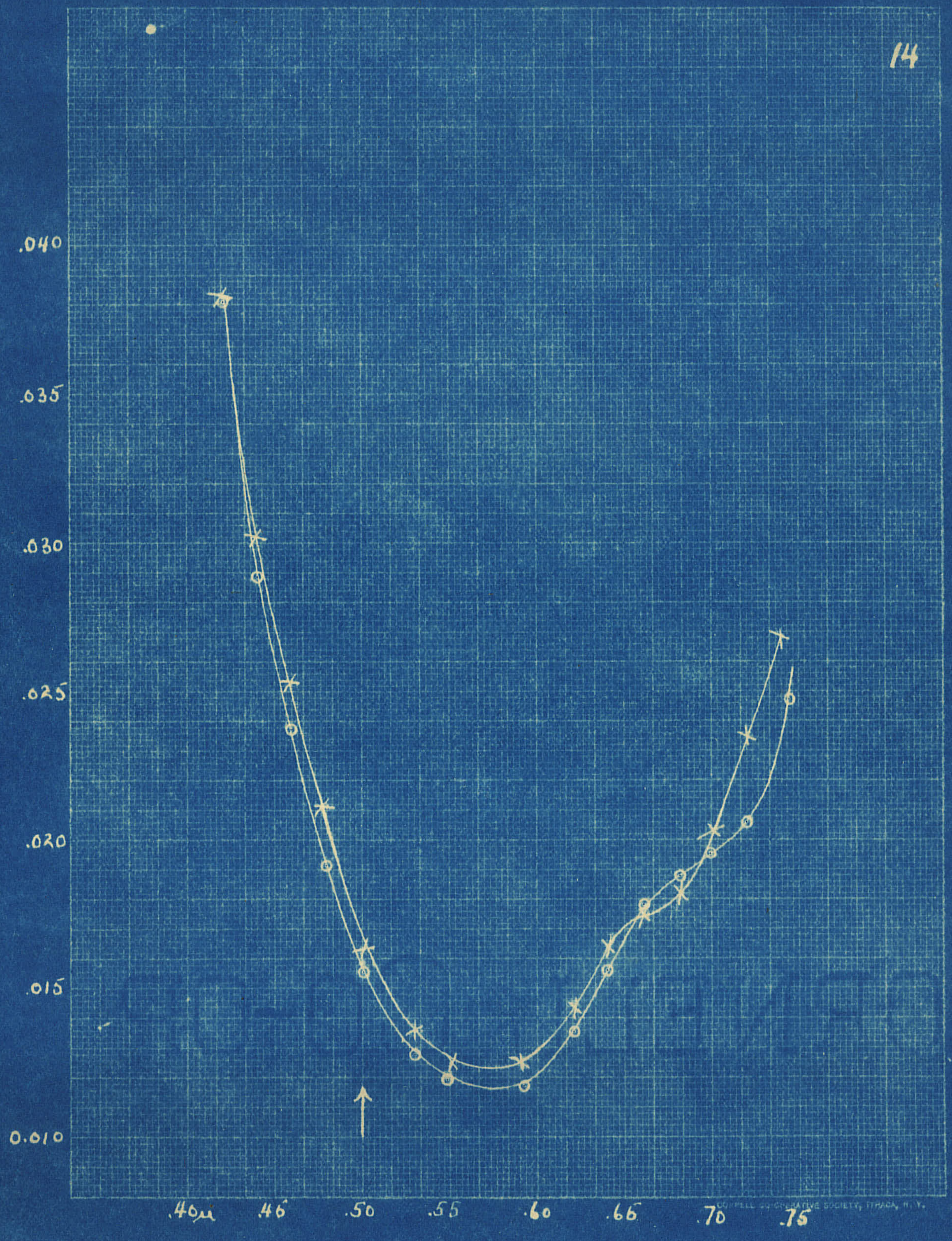


Fatigue Curve for .520μ Normal o–o Fatigue x–x



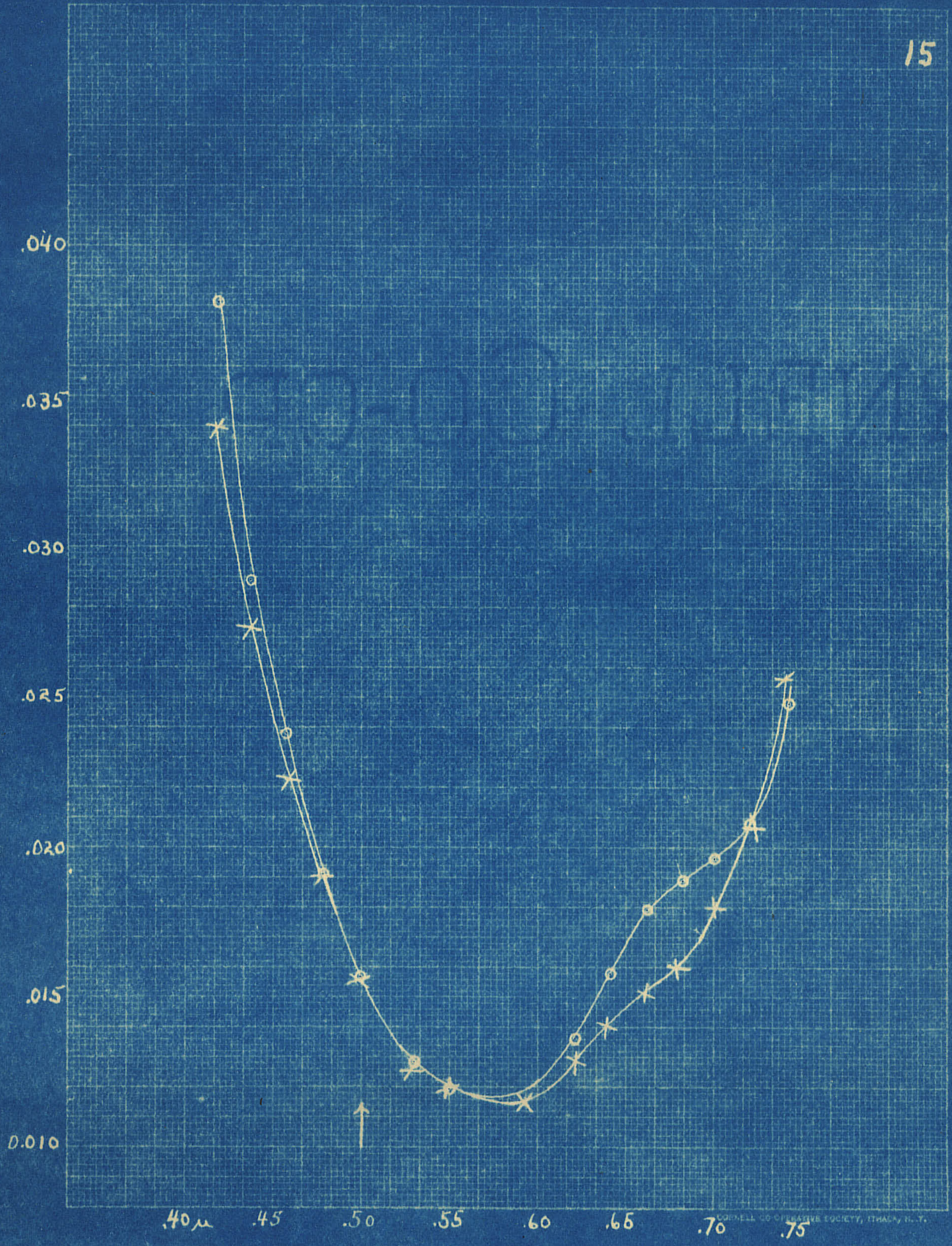
Reflex Curve for .520μ

Normal o—o
Reflex x—x

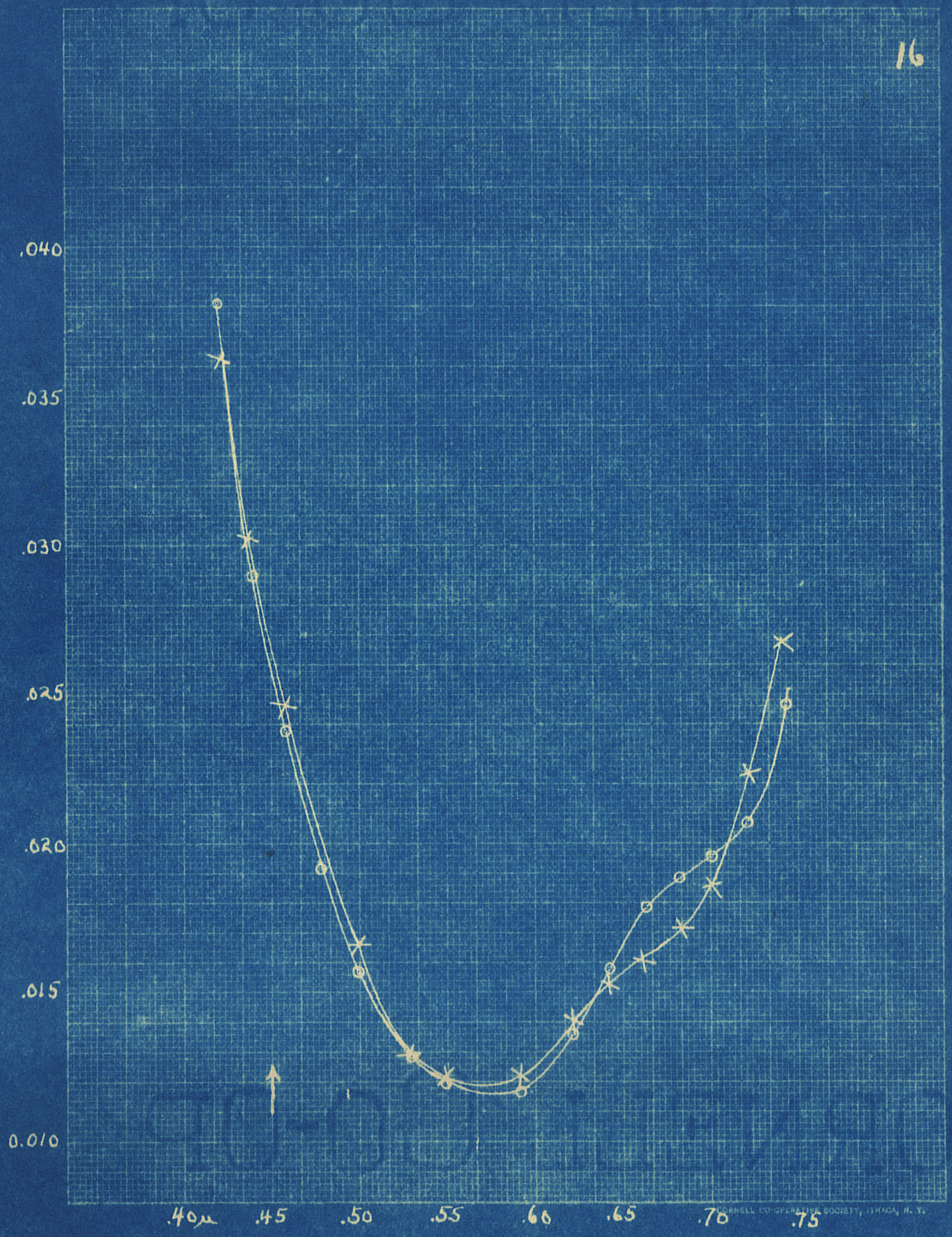


Fatigue curve for .505μ Normal o — o

Fatigue x — x

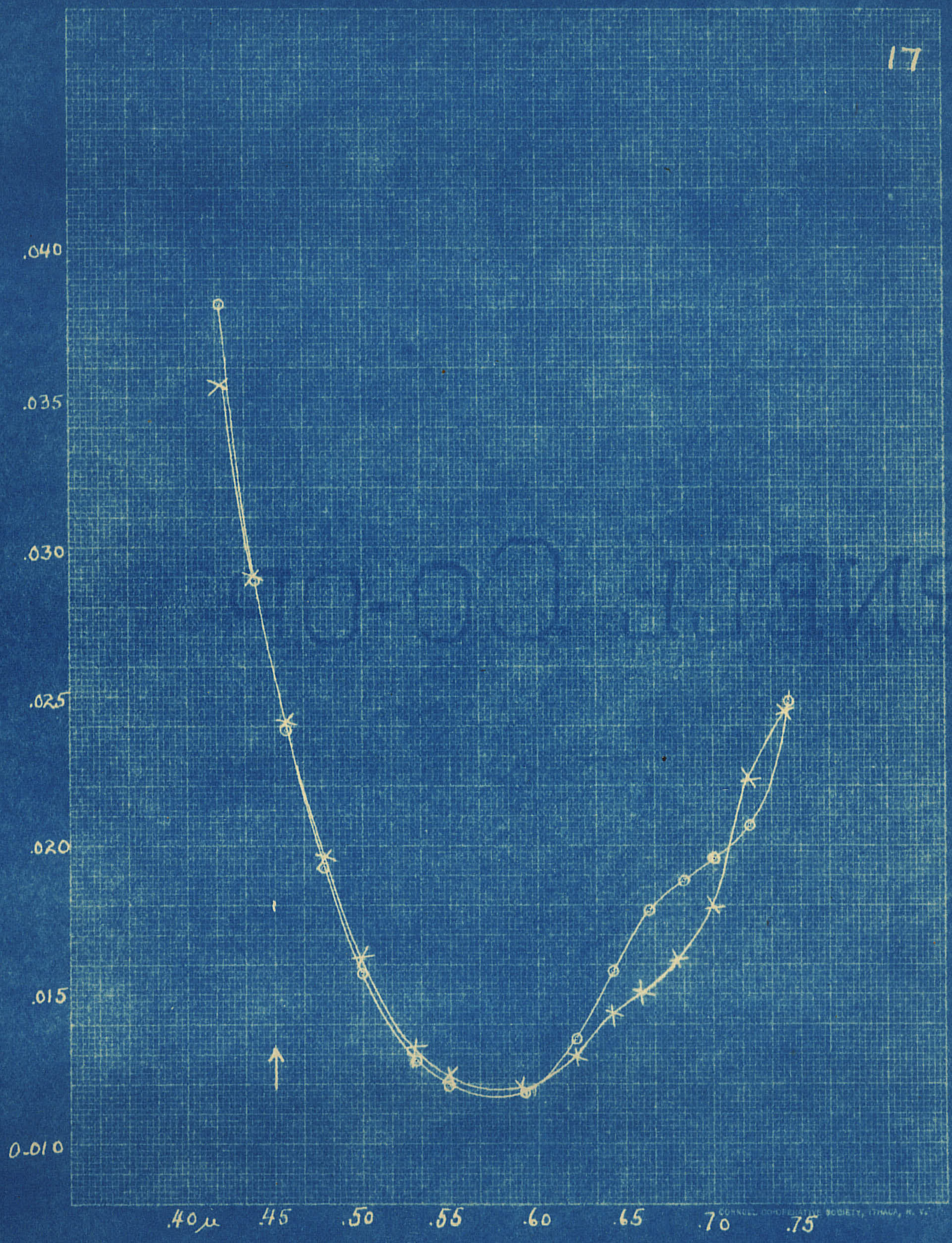


Reflex curve for .505μ Normal o—o Reflex x—x



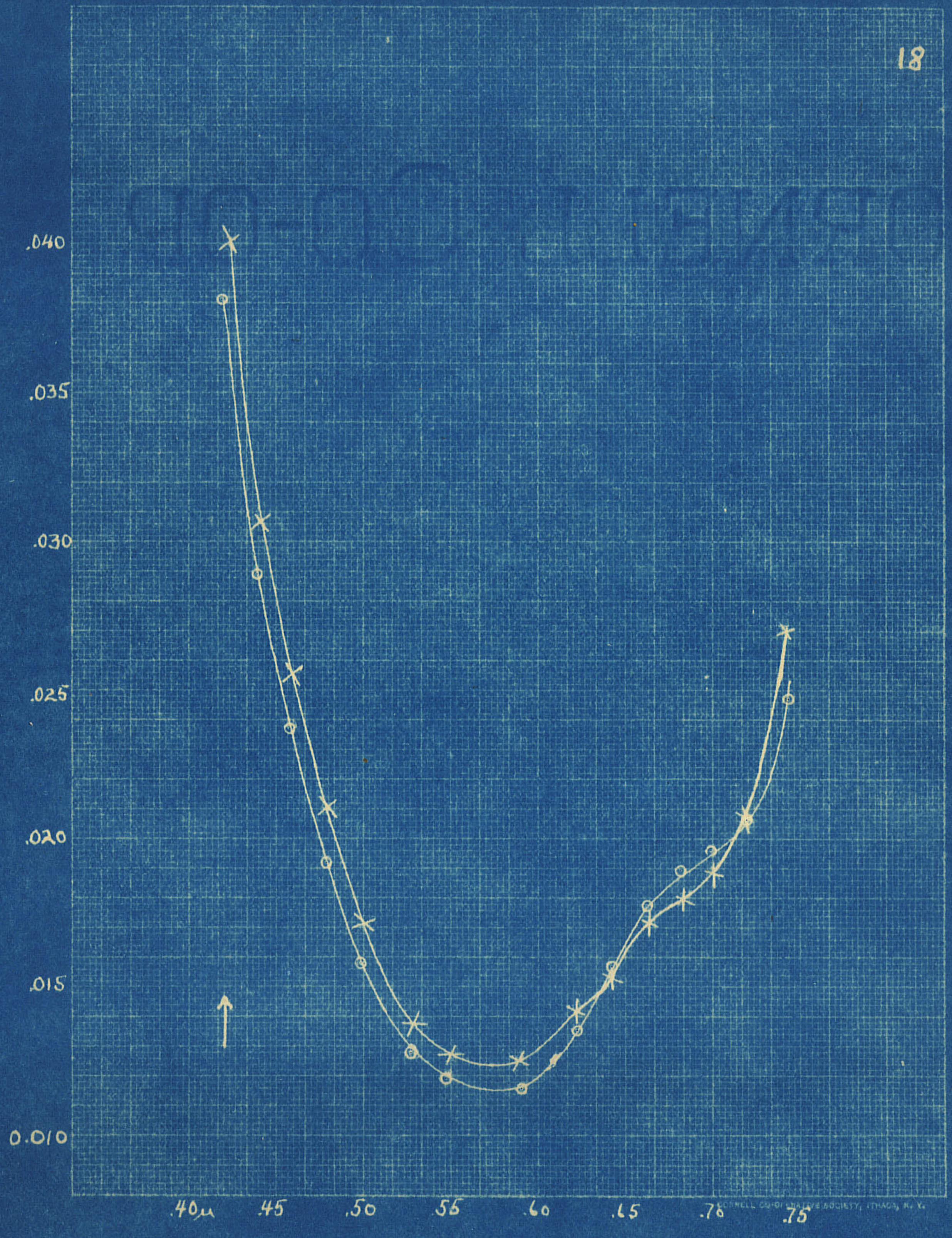
Fatigue curve for 450μ

Normal o — o
Fatigue x — x



Reflex curve for .450μ Normal o—o

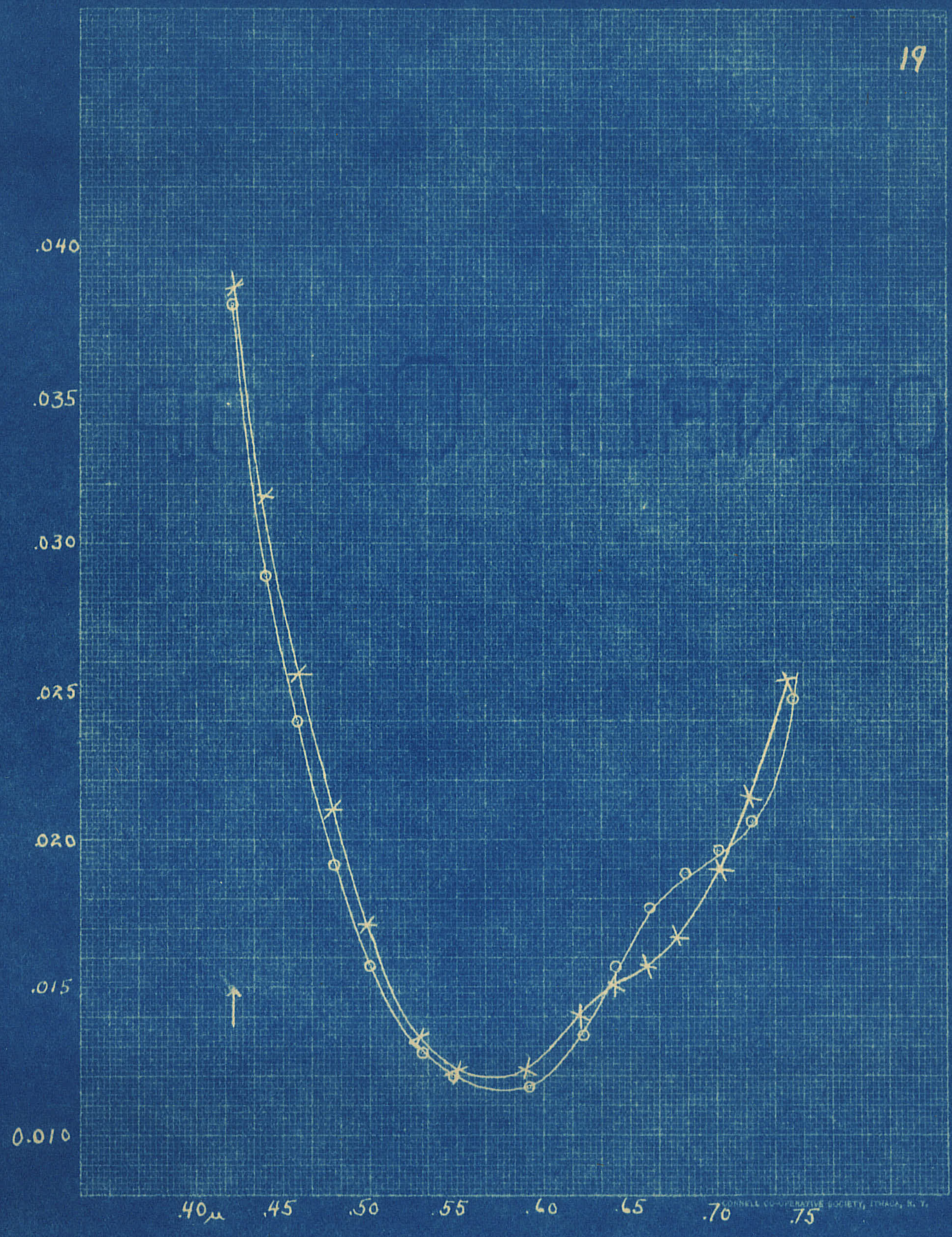
Reflex x—x



Fatigue curve for .425μ

Normal o—o

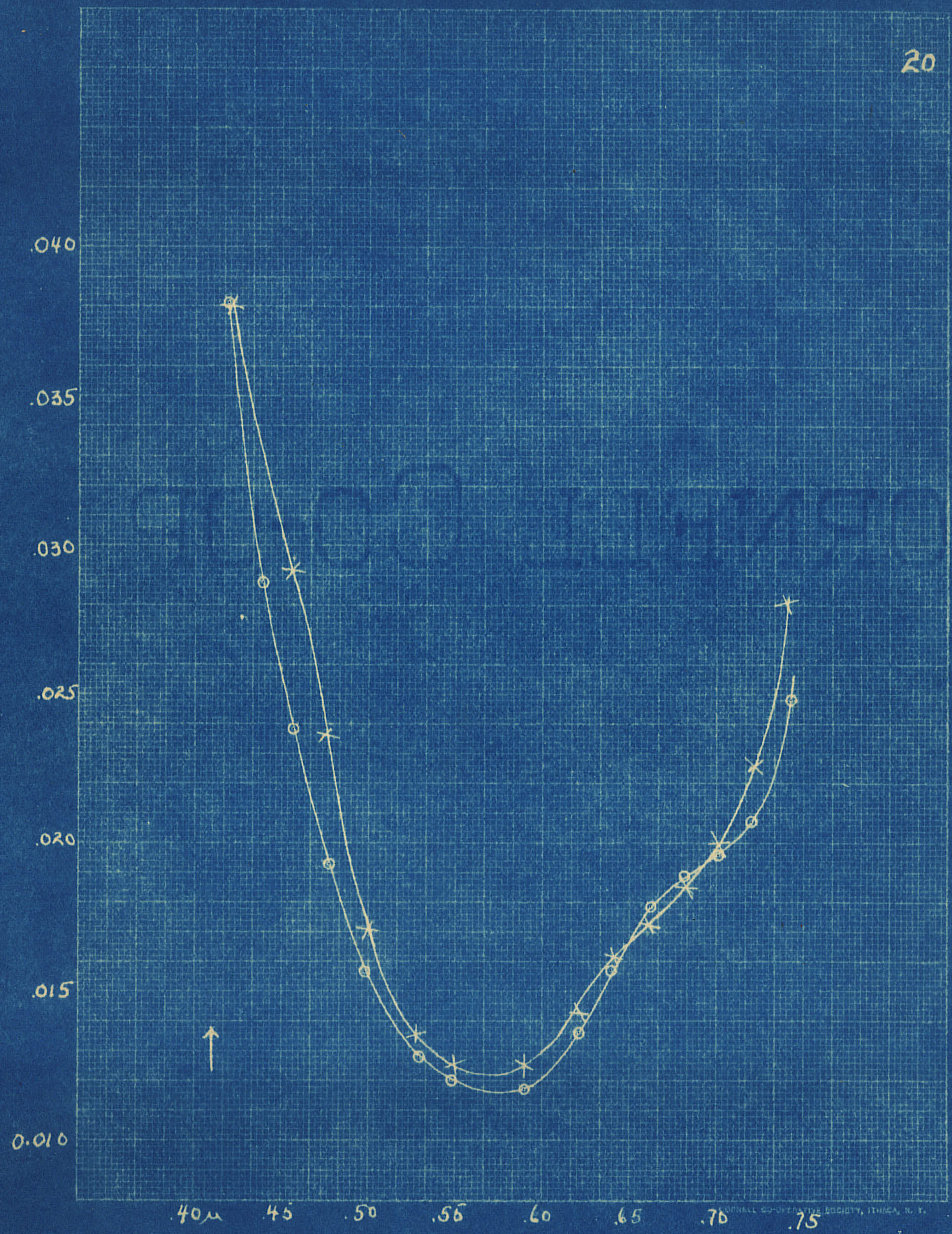
Fatigue x—x



Reflex Curve for .425μ

Normal o—o

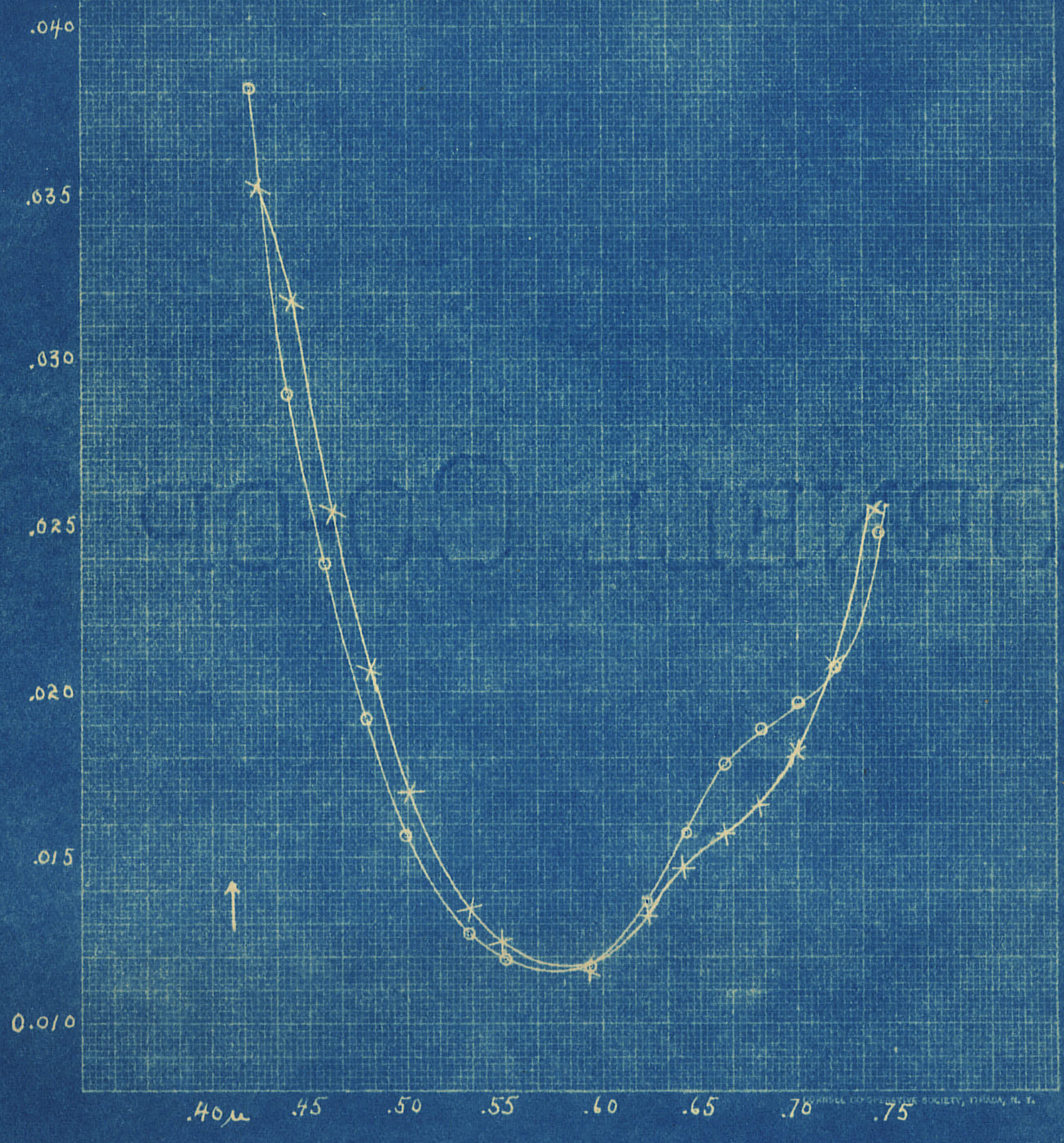
Reflex x—x



Fatigue Curve for .410μ

Normal o—o

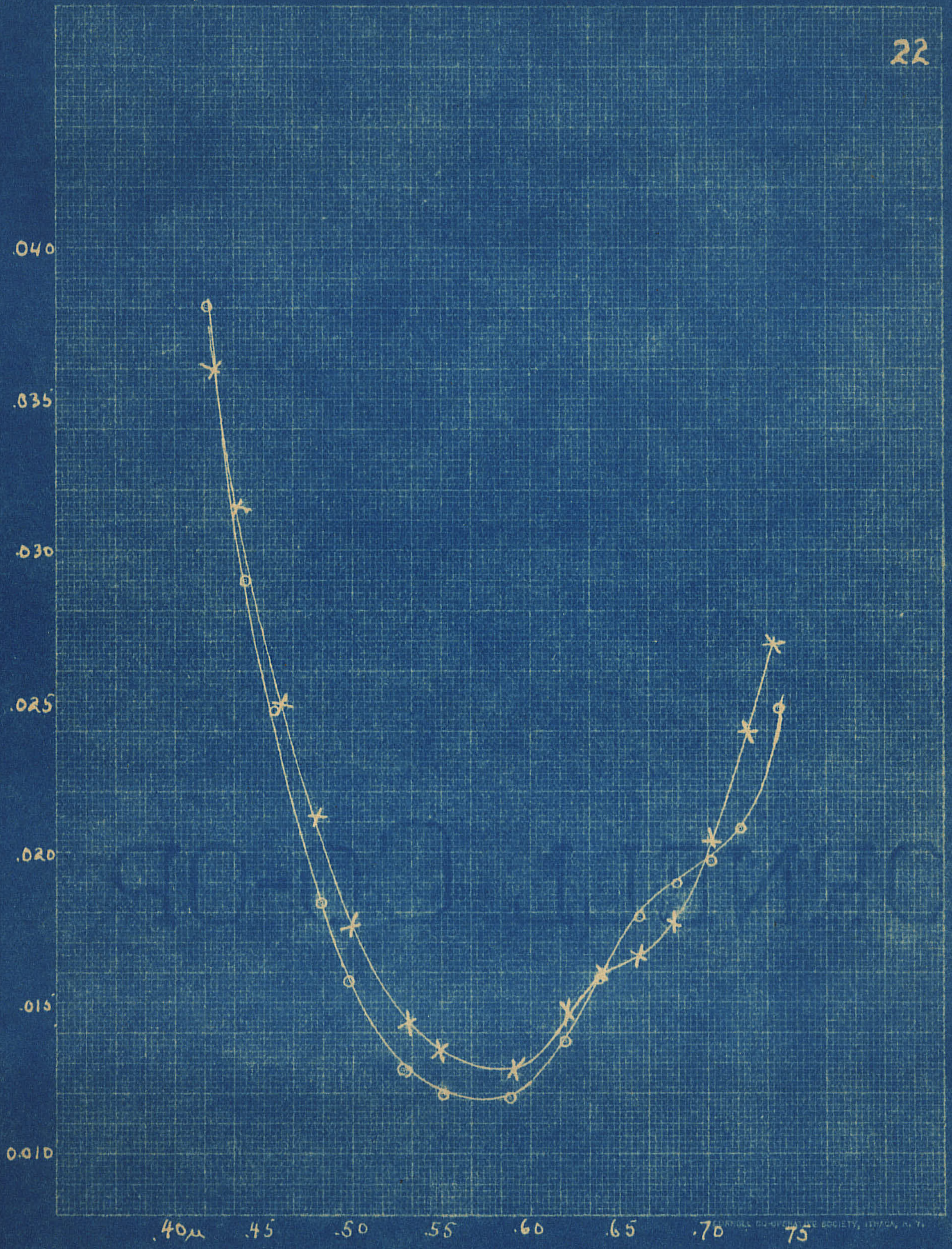
Fatigue x—x



Reflex curve for .410μ

Normal o—o

Reflex x—x



Normal Jan. 23rd o—o
Normal April 3rd x—x