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Introduction to Production Color Technology

by W. H. Edwards

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PROCESS ENGINEERING - PHILADELPHIA

E. I. DU PONT DE NEMOURS & COMPANY
INCORPORATED
FINISHES DIVISION
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The Finishes industry produces coatings used for both protective and decorative effects. A large portion of the manufacturing difficulties experienced by the Finishes industry resolve to the inherent problem of matching colors within commercially acceptable tolerances.

The users of pigmented coatings constantly desire new, different and more pleasing colors in practically every type of surface coating. This customer desire makes the development of new colors and color control during production a continuous source of formulation and manufacturing problems.

The importance of color, its fundamentals and applications, are understood only by a comparative handful of the people responsible for the development, manufacture, and sales of pigmented organic finishes. While the fundamental principles of the physics of color have been explored and are still being explored, little information has been published which is of practical value in dealing with the color problems inherent in the manufacture of pigmented finishes. As a result, the Finishes industry is burdened with the large amount of effort and expense involved in solving these color problems by largely trial and error experimental procedures.

The importance of color is emphasized within the du Pont Company by the increasing number of production departments which have active research and development programs in this field. Progress reports on these programs are exchanged at Company color conferences. In addition, the Fabrics and Finishes Department cooperates closely with these other departments and with the Engineering Research Laboratory in the development of new instruments for color measurement and calculation and in supplying "know-how" on the color control of pigmented products and dispersions.

The color program of the Fabrics and Finishes Department has now reached the point where new techniques are becoming available for application to routine production problems. The purpose of this course is to introduce and explain these techniques to production and technical personnel in order to pave the way for their successful use.

WHAT IS COLOR?

The term "Color" is used to describe a visual sensation which is not completely understood even by the most advanced researchers in the field. This visual sensation is initiated by a special form of energy known as visible light. Visible light creates the color sensation through the use of electromagnetic impulses having a wavelength between 400 and 700 millimicrons (a millimicron is one-millionth of a millimeter). The energy spectrum covers a broad range of other phenomena with which we are familiar. These phenomena differ from visible light mainly in their frequency or wavelength and vary from radio waves, which have a much longer wavelength than visible light, to X-rays and Gamma Rays, which have a much shorter wavelength. When the magnitude of the range of the entire electromagnetic spectrum is considered, the sensation of color is produced by a remarkably small segment of this spectrum.

When visible energy radiation from this segment enters the eye, it is converted into the sensation of color through a combination of physiological and psychological processes which have been and still are the subject of considerable scientific research. The sensitivity and accuracy of these processes which produce the color sensation are so remarkable that scientific technology has just recently succeeded in creating instruments which approximate or improve upon the human eye in the evaluation of color. These instruments are known collectively as "spectrophotometers".

WHAT ARE SPECTROPHOTOMETERS AND HOW DO THEY WORK?

Spectrophotometers are designed to measure color by analyzing the energy distribution or "spectral distribution" of the energy segment corresponding to visible light. This instrument is based upon the centuries old experiment of Newton who in the 1600's first used a glass prism to separate white light into its colored components. Mankind's ingenuity has taken the principles of the prism and created an improved form of prism known as a diffraction grating which is effectively made up of thousands of prisms per square inch. Nature has its own diffraction grating in the form of the minute water droplets in the atmosphere which turn the white light of sunlight into the analytical form of this light which we know as a "rainbow".

The use of the principles of the prism allowed man to break down light into its component wavelengths or colors. However, measurement of the intensity of each component wavelength and therefore of the color of the light was delayed until the "Electronic Age" and the development of a chemical cell which converted light energy into electrical energy which could be measured. This chemical cell is known as a photo-electric cell.

The spectrophotometer is an instrument which combines the principles of the prism, in the form of a diffraction grating, and the photo-electric cell to produce an analysis of color. The analysis produced by the spectrophotometer, known as a "spectrophotometric curve", is actually the analysis of the energy distribution of a specific light sample at each wavelength within the 400 to 700 millimicrons range as compared to the analysis of a reference beam of light. The color of the analyzed light is determined by the shape of the spectrophotometric curve. Spectrophotometers measure the color of a solid object by measuring the differences in the light reflected from the sample and a known reference. To understand why objects differ in color we must understand why visible light can differ in its spectrophotometric analysis.

HOW IS COLOR PRODUCED?

The color of an object results from the effect of certain chemical substances upon visible light. These chemical substances are known as pigments, dyes or stains and are either of natural or synthetic origin. The color of organic finishes is usually created by combinations of pigments, dyes, or stains, which impart color to a finish because of their basic molecular or crystalline structure, their particle size, and their particle size distribution. The basic color (i.e., red, green, blue or yellow) produced by a pigment, dye or stain is due to its molecular or crystalline structure.

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This color can be modified to a limited extent by variations in the average particle size and particle size distribution resulting from differences in the manufacturing or dispersion processes.

These pigment, dye or stain characteristics produce color through a combination of light reflectance and absorption. When a ray of light strikes a pigmented film it is broken down into its individual wavelengths. A portion of each wavelength component is either reflected or absorbed depending on the pigment characteristics discussed earlier. The absorbed light component is removed from the light rays and the reflected light, which determines the color of the film, is markedly different in spectral energy distribution from the light which strikes the film. For example, in Figure I, the visible light is shown broken down into five rough color components, violet, blue, green, yellow and red. When these color component light rays strike the surface of the pigmented film, a fixed percentage of each of the color component rays is reflected from the surface. This surface reflected light, which contains the same proportion of the five color components as the illuminating light source, is responsible for the phenomenon known as "specular gloss" or more commonly, and somewhat erroneously, just as "gloss".

Figure I

EFFECT OF LIGHT STRIKING A PIGMENTED FILM

The remaining portion of each of these color component light rays penetrates into the film until it strikes a pigment particle. Since the film in this example is pigmented with "red" pigment particles, a portion of the red light component will be reflected from the pigment particle. However, the violet, blue, green and yellow color component light rays which strike the "red" pigment particles are absorbed into the pigment. Thus, under ideal circumstances, only the red light rays would eventually emerge from the film and produce the "red" color. In actual practice, small percentages of the violet, blue, green and yellow light rays are also reflected by the "red" pigment and eventually emerge from the film along with a considerable percentage of the red light rays.

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If the spectrophotometer were to analyze the light emerging from the film of Figure I, the spectrophotometric curve produced by this analysis would look like the top curve in Figure II, where the intensity of the emerged light at each wavelength is plotted on the vertical scale versus the wavelength of this emerged light. If the pigmentation of the film had been composed of "green" pigment instead of "red" pigment, the bulk of the light emerging from the film would have been composed of the green light rays and the resulting spectrophotometric curve would look like the center curve in Figure II. Similarly, the use of a "blue" pigment in the film instead of the "green" or "red" pigment would result in the spectrophotometric curve shown at the bottom of Figure II.

Figure II
Spectrophotometric Curves
of Colored Pigments

Inspection of the three spectrophotometric curves of Figure II indicates that the "peaks" of the curves of the different colors occur at different wavelengths. The color of a pigmented film can be roughly determined by the wavelengths included in these peaks. The spectrum has been more or less arbitrarily divided into six broad regions; violet, blue, green, yellow, orange and red. This classification of spectral colors is only approximate because of considerable overlapping. A more precise classification is provided by the wavelength scale upon which the six regions of colors are designated as follows:

Violet	extends	from	400	to	460 millimicrons
Blue	"	"	460	"	500 "
Green	"	"	500	"	570 "
Yellow	"	"	570	"	590 "
Orange	"	"	590	"	610 "
Red	"	"	610	"	700 "

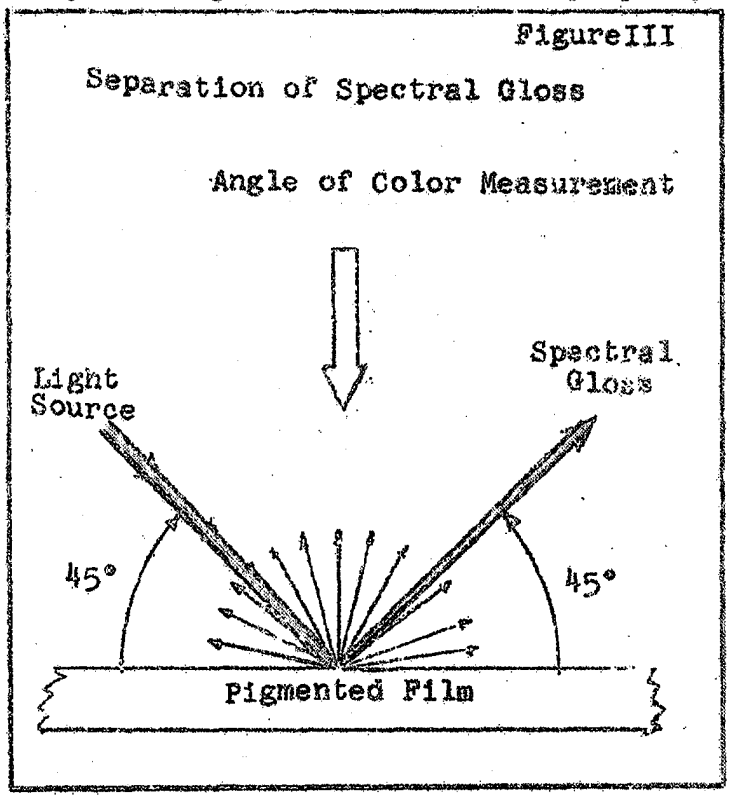
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The Influence of Spectral Gloss on Color and Color Measurements

As mentioned earlier, a portion of the component light rays striking the surface of the pigmented film are reflected with essentially the same visible light composition as that of the light source (spectral gloss). Any mixture of the light composing the spectral gloss with the light emerging from the film will produce a light of changed color component composition. Because of this factor, color measuring instruments are designed to eliminate the possibility of mixing spectral gloss light reflected from high gloss planar surfaces with the light emerging from the film. This separation can be made readily through the selection of the proper geometrical viewing conditions. Spectral gloss has one basic property which makes this separation possible. The angle at which the light rays strike the film surface equals the angle at which the specular gloss component is reflected. (Note Figure III.)

Figure III

Separation of Spectral Gloss



Conversely, the light rays emerging from the film have been so scattered by their reflectance from the pigment particles in the film that they emerge from the film surface in a completely scattered or diffused condition, providing uniform intensity at every angle.

Color measuring instruments are designed to take advantage of these differences in the physical character of the specular gloss component and the light emerging from the pigmented film. In a typical design, the light source is located so that the light rays strike the surface of the film at an angle of 45° and the gloss component is reflected at the opposite 45° angle. The measuring phototube is located to receive the light emerging from the film at a near perpendicular (90°) angle.

While this configuration gives accurate measurements when applied to high gloss samples with a perfectly smooth or planar film surface, the use of a "flattening agent" or a film pigmentation level which roughens the surface of the film will result in an erroneous measurement of the color characteristics of the pigmented film.

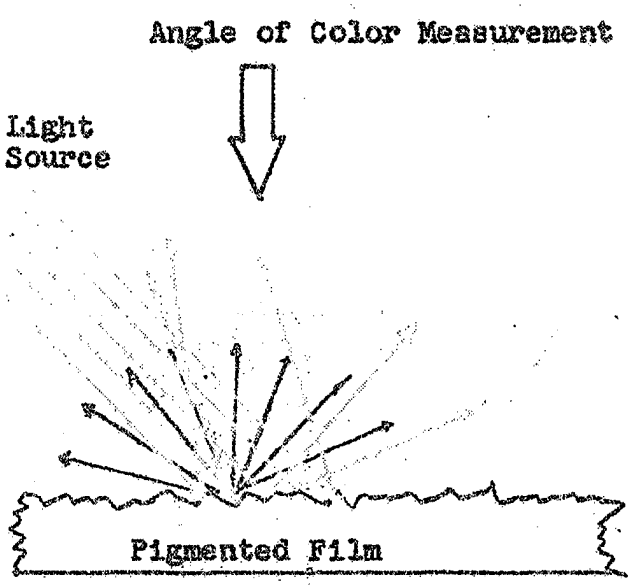
This erroneous measurement results from an increase in the intensity and a change in the wavelength distribution of the measured light from the film due to a mixture of a portion of the specular gloss with the light emerging from the pigmented film. (Note Figure IV.)

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This mixture of the specular gloss with the light emerging from the pigmented film is due to the scattering of the spectral gloss component by the irregularity of the pigmented film surface. The amount of this gloss component in the measured light from the pigmented film is a function of the irregularity of the pigmented film surface.

FIGURE IV

Effect of Low Gloss on Measured Light



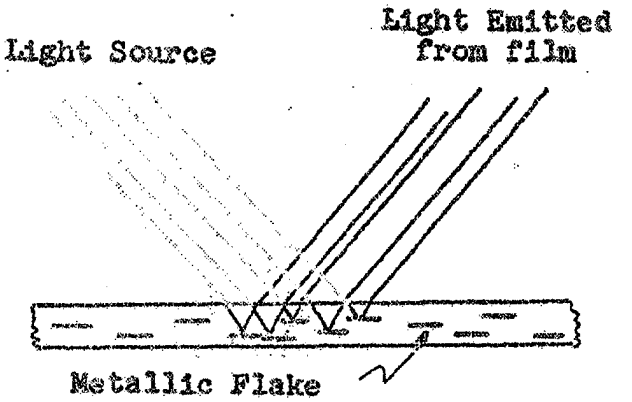
METALLIC COLORS

Metallic colors differ from conventional non-metallic colors by virtue of their pigmentation, which is composed of metallic flake particles and transparent colored pigment dispersions. Metallic colors rarely contain pigments whose average particle size is large enough to scatter light in the film, but depend instead on the orientation of the metallic flake to obtain the required degree of hiding. This metallic flake is usually aluminum, although colored bronze powders, stainless steel flake or even certain mineral flake-like particles are sometimes employed.

The function of this flake when dispersed throughout the film, is to act as a series of tiny individual mirrors which reflect the light penetrating into the transparent colored film. The orientation of these "mirrors", coupled with the planarity or flatness of the flake surface is of primary importance in determining the directional intensity of the reflected light. Because of the directional intensity of the light reflected from the flake, the color of metallic-type finishes has a directional effect, known as "two-tone" or "flop". (Note Figure IV-A.)

FIGURE IV-A

Color Mechanism of Metallic-Type Colors



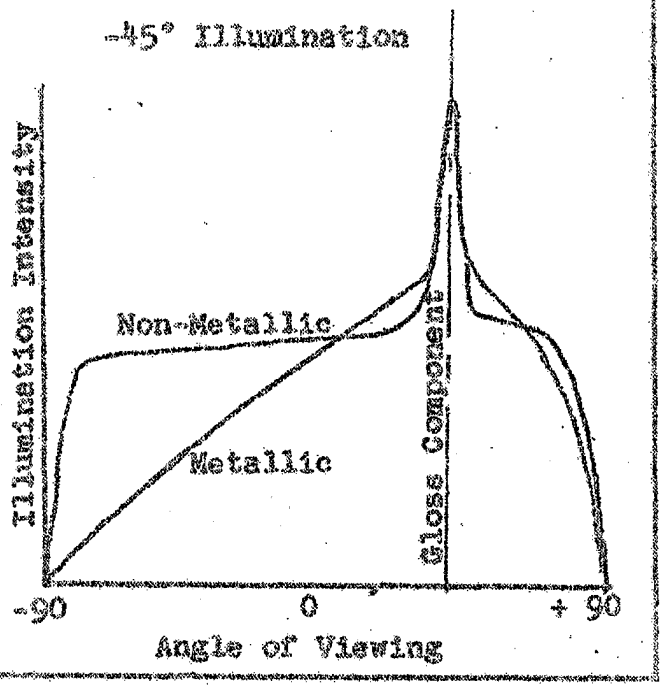
These finishes achieve this characteristic of "two-tone" because almost all of the light is reflected at a relatively narrow angle and very little light is reflected or diffused to the side.

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A typical intensity curve measuring reflectance against the viewing angle is shown in Figure IV-B. From this curve it may be seen that since little light is reflected to the side, these colors will become progressively darker as they are rotated more parallel to the direction of viewing. Instrumentally, it is possible to characterize "two-tone" as the difference between the light intensities reflected at the two angles of viewing where the maximum and minimum intensities of reflected light are found. A "two-tone" meter has been designed on this principle by J. G. Schreckendgust of the Marshall Laboratory. This instrument is based upon experimental data obtained by G. C. Bell of the Marshall Laboratory.

FIGURE IV-B

Typical Light Reflectance Intensity Curve of Metallic Film



The basic theoretical difference between metallic and non-metallic colors is found in the directional intensity of the light leaving the film of metallic finishes as compared to the diffuse reflection leaving the surface of the non-metallic film. In theory, if the metallic flake particles were perfectly flat and orientated in the film parallel to the film surface, and if the transparent pigment dispersions used were free of particles large enough to scatter light, the "two-tone" of these colors would be at a maximum since no light would be reflected from the surface at oblique angles.

In practice, however, this maximum "two-tone" is rarely achieved. In the first place, the surface of metallic flake particles is never perfectly flat, but is somewhat irregular due to the conditions under which the metallic flake is produced and dispersed. This surface irregularity is more predominant in smaller flake particles, which lose much of their ability to act as individual mirrors.

The orientation of metallic flake particles is not uniformly parallel to the film surface, but varies widely depending on the spraying conditions. Smaller flake particles, in particular, show a lack of uniform orientation. This lack of a uniform orientation coupled with the surface irregularity of the flake particles does much to spread out the desired directional reflectance of metallic finishes to somewhat approach the diffuse reflectance of non-metallic finishes.

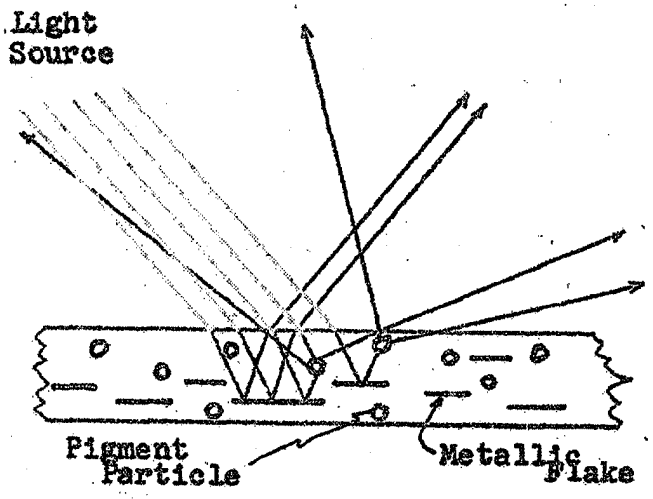
A third factor contributing to the colorimetric imperfection of metallic films is found in the transparent pigment dispersions with which the film is colored. These transparent pigment dispersions actually contain varying quantities of pigment particles which are large enough to scatter light, and therefore to superimpose a diffuse effect over the directional effect of the metallic color

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film. (Note Figure IV-C) These larger pigment particles result from the pigment manufacturing process, the dispersion process or pigment flocculation within the drying film. Because the quantity of pigment particles large enough to scatter light may vary widely from batch to batch, all metallic-type colors which must be reproducibly manufactured should contain at least trace quantities of a pigment which is highly light-scattering (such as a Titanium Dioxide white) in order to allow adjustment of the color for variation in the number of light-scattering pigment particles found in the transparent colorants used.

FIGURE IV-C

Effect of Large Pigment Particles In Metallic Color



Development of Mathematical Color Coordinate Systems

The successful development of the spectrophotometer allowed the definition of color in terms of the spectral composition of the light emerging from a pigmented film. Since this spectrophotometer curve was not readily translateable into an acceptable visual color network, it was necessary to develop methods which would allow correlation between these spectral composition curves and color as seen by the eye. In order to achieve this goal, it became necessary to agree on various factors which control the measurement, viewing and recording of spectrophotometric curves. This agreement was reached at the 1931 International Color Conference, where many standards influencing future work on color measurement were established. The three C.I.E. standards most applicable to the correlation of color measurement with visual response are:

1) Distribution coefficients to provide the amounts of three color stimuli required to match the color matching characteristics of the average eye.

2) Reference stimuli relative to which the distribution coefficients can be mathematically transformed and in terms of which standard color specifications can be expressed. (The C.I.E. color coordinate system.)

3) Since the human eye will measure as "just perceptible" color differences of varying magnitude under different conditions of illumination, three illumination standards were established.

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Source A: Gas filled incandescent lamps - color temperature 2,854° Kelvin.

Source B: Noon Sunlight - color temperature 4,870° Kelvin.

Source C: Overcast Sky Average Daylight - color temperature 6,740° Kelvin.

The color temperature of a light source is the temperature at which the walls of a furnace should be maintained to produce a radiation which duplicates the color spectrum of the desired light source.

These standard light sources were incorporated into "standard" light booths where the conditions of light intensity and viewing conditions were more or less standardized. Source C is widely used throughout the Finishes industry because it most nearly represents the average conditions under which pigment films are viewed. The color characteristics of Source C are incorporated into the design of the differential colorimeter and other tri stimulus colorimeters used in the Finishes industry in order that their analysis of the color characteristics of a given sample will agree closely with the visual interpretation of the "average" color observer.

However, it should be remembered that these light sources have been selected to reproduce visual sensitivity corresponding to the average conditions of illumination. The sensitivity of the eye will be changed by increasing or decreasing the intensity of light on a given color. For example, in the development of very dark black pigment dispersions (less than 1% light reflectance) the small amount of light reflected under normal viewing conditions did not allow an accurate visual assessment of the hue and saturation differences to be made. The use of a 1000-watt projector as a source of illumination increased the intensity of the reflected light to the point where accurate visual interpretation of color differences could be made.

The C.I.E. coordinate system, for all its technological advantages, lacked the one basic ingredient necessary to make it universally acceptable for routine color development and control work; it was not a visually uniform system, In other words, the C.I.E. system showed visually equal color differences as being considerably different in magnitude; Industry required a color coordinate system wherein the instrumental assessment would directly agree with the visual assessment.

The framework for such a color coordinate system was available in the classical Munsell system of supposedly visually equidistant color specimens. This system has been mathematically interpreted by a number of individuals. Most of these mathematical coordinate systems give a good representation of the Munsell color solid in the region in which the researcher was interested but are inaccurate in other portions of the solid. The closest agreement to the Munsell color system among the classical mathematical systems is given by the Adams' coordinate system.

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These mathematical coordinate systems define the color solid in terms of the lightness, hue and saturation concept.

Lightness is defined as the total reflectance of Source C light from the pigmented film as viewed directly from above when the film is illuminated from a 45° angle. Lightness in the color coordinate system is defined as a value of visually neutral gray between pure white or total reflectance (lightness = 100) and pure black of zero reflectance (lightness = 0). The intermediate neutral grays, by definition, are free from any value in the other two color directions (hue and saturation). "Colored" pigmented films possess this characteristic of lightness plus their hue and saturation components which give them "color" characteristics.

Hue - If the lightness axis is considered as an axle, the hue and saturation may be considered as elements of a spoked wheel which can slide up and down to any position (lightness) on the calibrated axis. (Note Figure V.) The hub of the wheel represents the neutral gray of no hue or saturation. The spokes radiating from this hub are representative of the various hues. The selection of one spoke as a fixed hue (i.e., red) will allow the location of all of the other spokes (hues) to be expressed in terms of angles from the fixed hue.

Figure V

The Adams' Color Coordinate System

Saturation is expressed as the length of any given hue (spoke). A short spoke would indicate a color which is approaching neutral gray, while progressive lengthening of the spoke would indicate an increasingly cleaner or more saturated color of the same hue.

The classical Adams' Coordinate System has been modified by the du Pont Company Engineering Research Laboratory (ERL) to give almost precise agreement with the Munsell Visual Color System. This modified Adams' Color Coordinate System eliminates the angular hue of the original Adams' System

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by using the directly calculated rectilinear coordinates "a" and "b" to express the angular hue and saturation in a more easily calculated and visualized form. If we take two sheets of cardboard and cross them at right angles to form an "X" (note Figure VI) the rectilinear form of the Modified Adams' Coordinate System may be visualized. The straight line formed by the intersection of the two pieces of cardboard is the axle of the spoked wheel model and is the lightness (L) coordinate, representing all visually neutral grays between pure white and pure black. The sheets of cardboard represent the other two coordinates "a" (red-green) and "b" (blue-yellow).

Figure VI
The Modified Adams' Coordinate System

If we look directly down on these crossed pieces of cardboard, they will appear as straight lines a-a and b-b which cross at right angles (90°). These lines represent the red-green (a-a) and blue-yellow (b-b) axes of the color solid. Any color point having modified Adams coordinates (a,b) may be plotted on this a-a, b-b coordinate system and the visual hue and saturation determined. The hue angle (θ) with respect to the b-b axis is determined by the following equation:

$$\text{Tangent } \theta = a/b \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (I\text{-}1)$$

The saturation of point (C), i.e., the distance between the point (a,b) and the neutral axis (a = 0, b = 0) is defined by the following equations for the determination of the length of the hypotenuse (saturation) for a right angle triangle as the lengths of its two sides (a and b).

$$\text{Saturation } (S) = (a^2 + b^2)^{1/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (I\text{-}2)$$

The extremities of the color solid are irregular in shape with the saturation being theoretically limited to the saturation obtained with pure monochromatic light at each hue and lightness.

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In practice, the saturation limit of the color sphere is limited to the maximum saturations obtainable with the various pigments. As newer, more saturated pigments are constantly being synthesized and introduced, the usable saturation limit of the color sphere is constantly expanding toward the theoretical saturation limit.

The Modified Adams' Coordinate System is based on the following equations:

$$L = 10\,V\,(G) \quad \text{.....} \quad \text{(I-3)}$$

$$a = a_{R'} - a_G \quad \text{(I-4)}$$

$$b = b_G - b_B \quad \text{(I-5)}$$

where:

$$a_G = 41.86\ V\ (G) \quad \text{(I-6)}$$

$$a_{R'} = 41.86\ V\ (R') \quad \text{(I-7)}$$

$$b_B = 16.74\ V\ (B) \quad \text{(I-8)}$$

$$b_G = 16.74\ V\ (G) \quad \text{(I-9)}$$

R' = $0.78(R) + 0.22(B)$ sometimes rounded off to $0.8(R) + 0.2(B)$ (I-10)

V = Emperical fifth order polynomial equation derived to express the relationship between tristimulus reflectance and Munsell value.

(G) (R) (B) = Tristimulus readings of the green, red and blue reflectances obtained with the light source/filter/photo-tube combination of the "Colormaster" Differential Colorimeter.

Tables have been prepared covering equations (I-3), (I-6), (I-7), (I-8) and (I-9). These tables (Table I in the volume of tables) reduce the actual physical calculation to equations (I-4), (I-5) and (I-10).

The Problem of Color Terminology

The systematic evaluation of the reactions of the "average" color observer has led researchers to the conclusion that color is essentially a three-dimensional solid. Since color is a three-dimensional phenomenon, a given color must be related to a second color by three visual differences. Many terms used to express these differences are misleading because of the various meanings associated with them. The term "dirty" for example, can mean less saturated, darker or a combination of both of these color directions. Other terms of a similar type are:

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"Paler"	-	could mean lighter and grayer or whiter.
"Deeper"	-	could mean darker or more saturated or both of these color directions.
"Cleaner"	-	could mean lighter or more saturated or both of these color directions.
"More Brilliant"	-	could mean lighter or more saturated or both of these color directions.
"Dirty", "Blacker" and "Dusky"	-	could mean darker or less saturated or both of these color directions.

The terminology used to define the three color dimensions in a color solid is confusing, not from the standpoint of a duplicity of meaning, but from the large number of terms which have the same dimensional meaning. Saturation, for example, is called "Chroma" in the Munsell System, "Degree of Chromaticity" in the Villa Lobos and Harmony Systems and "Purity" in the C.I.E. System.

In order to overcome the communication problem caused by the multiple meaning of certain color descriptive terms, the lightness, hue, saturation terminology previously defined is recommended as standard for all departmental correspondence.

These three terms are used to define the basic color characteristics of any color. In addition to hue, saturation, and lightness, two other color characteristics are often used in the classification of color.

1. "Two-Tone" - (Sometimes called "Flop" or"Side-Tone") This characteristic of color is found when certain colors, particularly those containing metallic aluminum particles, are viewed from a variety of angles. The effect is believed due to changes in the intensity of the reflected light caused by the scattering of light within the pigmented film and reaches a maximum when the pigment particles are within a certain size and distribution range.

   Our investigations into the causes of "Two-Tone" differences have led to the conclusion that the magnitude of the "two-tone" effect produced by a single colored pigment dispersion is controlled by two factors; the transparency of the pigment dispersion and the masstone lightness of this dispersion. An increase in the "two-tone" characteristics can be obtained by either an increase in the transparency or a reduction in the masstone lightness of the dispersion.

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2. Metamerism - When two colors look identical under one condition of illumination and different under other types of illumination they are said to be metameric. This condition is usually due to differences in the chemical composition and particle size distribution of the pigments used in formulating the two colors, which changes the wavelength distribution of the absorbed and reflected light from these colors. Typical examples of metamerism are found in cases when "Duco"* dry plate standards are used for "Dulux"* colors of different pigment composition. Considerable difficulty has been experienced in matching production colors under these conditions. Metamerism can usually be eliminated through the selection of the same type of pigment for each color match.

The Potential of Visual Coordinate Systems

Mathematical color coordinate systems, based upon the visual reaction of the human eye, are primarily intended to assess color differences existing between a standard and a batch in terms of visual uniformity existing throughout the visual color solid. As such, the Modified Adams Coordinate System is designed to replace the human eye in the visual judgment of color differences. The National Bureau of Standards has established a measure of visual color difference known as the National Bureau of Standards (NBS) unit. A well-trained color observer, under ideal lighting conditions, can detect a color difference of 0.3 NBS units. However, in many cases it is impossible to accurately assess, with the human eye, the color difference in terms of the lightness, hue and saturation characteristics of color. The use of a color measuring instrument, such as the "Colormaster" Differential Colorimeter, along with the Modified Adams Coordinate System and the proper measurement techniques makes possible the determination of the overall color difference (ΔE) and its lightness, hue and saturation components from the following equations:

$$\Delta L = L\,(\text{Batch}) - L\,(\text{Standard}) \quad \text{(I-11)}$$

$$\Delta a = a\,(\text{Batch}) - a\,(\text{Standard}) \quad \text{(I-12)}$$

$$\Delta b = b\,(\text{Batch}) - b\,(\text{Standard}) \quad \text{(I-13)}$$

$$\Delta E = (\Delta L^2 + \Delta a^2 + \Delta b^2)^{1/2} \quad \text{(I-14)}$$

where:

ΔL = difference in lightness between the batch and the standard.

Δa = difference in the a component of the hue and saturation between the batch and standard.

Δb = difference in the b component of the hue and saturation between the batch and standard.

(*) Du Pont Registered Trademark

The application of instrumental methods of color to the measurement and control of production color matching has been largely confined in the F. & F. Department to the shading of high-bake whites and the selection of tinting bases for the Mixing Machine refinish system. There are two reasons for this limitation:

1) The calculation of ΔE, ΔL, Δa and Δb values by hand is time-consuming (est. 10 minutes) even with the tables of Modified Adams Coordinate. Also the many calculation steps are conducive to human error.

2) There is virtually no data on the numerical color difference which constitutes a commercially acceptable color tolerance. This is not to be confused with the well-defined "visual color difference".

These limitations have been largely overcome through the development by the Engineering Research Laboratory, under F. & F. Department commission, of a "Color Difference Computer" which calculates ΔL, Δa and Δb directly from the G, R and B values of the batch and the standard. The prototype of this machine is currently under evaluation at Toledo where it is being used experimentally in the shading of colors and in the determination of the color difference inherent in a "Commercial Color Match".

The production of pigmented finishes rarely achieves an exact color match to the standard. As a result the concept of the "commercial color match" has been developed to express the color deviation which is acceptable in commercial production. The magnitude of the color deviation allowable in a "commercial color match" is dependent upon two factors: the use of the pigmented finish and the area of the color solid in which the color is located.

Pigmented finishes designed for production line application to mass produced consumer items such as automotive and appliance finishes have a "commercial color tolerance" which is very restricted in visual color difference. The purpose of this restricted color tolerance is to insure that parts which are separately finished with different batches of the same color can be assembled without the possibility of an objectionable color difference between the pre-finished components.

Pigmented finishes which are designed for application to a completed mechanism such as some industrial finishes and trade sales products are manufactured to relatively broad color tolerances because there is no need to obtain a close color match for separately finished and assembled components.

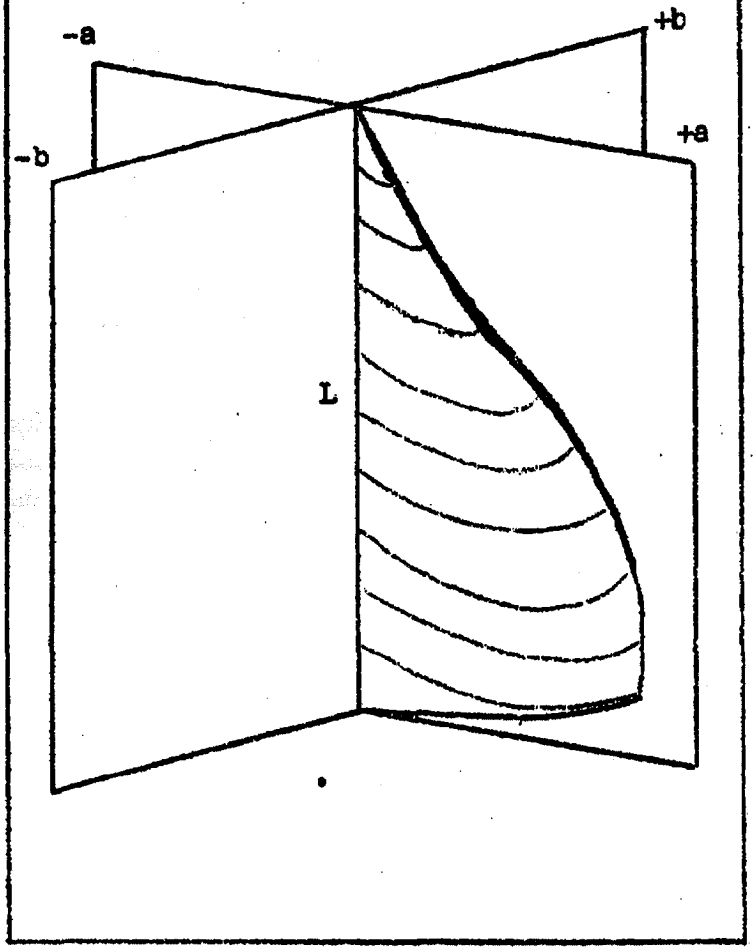
In addition to the variation in the magnitude of the commercial color tolerance with the intended end use of the pigmented finish, the tolerance also varies with the color. In general, the magnitude of the "commercial color tolerance" increases as the color becomes darker. This changing tolerance for a given type of pigmented finish indicates that the visual tolerance for color is not uniform throughout the visual color solid.

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Limitations of Visual Coordinate Systems

The ultimate objective of the F.& F. Department's color program is the routine preformulation and shading of production batches. In order to understand why the visually uniform coordinate systems, as exemplified by the Modified Adams Coordinate System are not suitable for preformulation and shading calculations, let us take a given colored pigment dispersion, such as 253-0312, and let it down in varying proportions with white. (Note red curve in Figure VII.) It is possible to select various color/white combinations corresponding to lightness values of 90, 80, 70, 60, 50, 40, 30, 20 and 10 and to combine each color/white combination in varying proportions with a black/white combination of the same lightness. (Note green curves in Figure VII.) Examination of the results indicates that the locus of the colors produced with combinations of the red pigment dispersion, white and black is actually a complex shape. This shape reflects the non-linear response of the human eye to variations in the pigment composition. If we take a slice through the color solid at a lightness value of 50 (note Figure VIII) and look down on the color solid, it is possible to examine the effect of combining a neutral gray of lightness 50 with various color/white combinations of lightness 50.

Figure VII
Color Blends in the Visual Color System



Inspection of Figure VIII indicates that the change in visual hue with increasing saturation is consistently clockwise in one-half of the visual color solid and consistently counter-clockwise in the other half of the color solid. While the effect of only a handful of pigments is shown for the sake of clarity, all pigments and pigment combinations studied to date conform to this pattern.

If a series of slices of the color solid spaced at increments of ten units of lightness is superimposed over the L = 50 slice of the previous figure, the result is shown in Figure IX.

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Examination of this figure indicates that the visual hue not only varies with a change in saturation but also with a change in lightness. If the saturated ends of each lightness curve, corresponding to the locus of the color/white combination at that lightness, are connected, the result is the characteristic "loop" produced by color/white blends.

Figure VIII

The Visual Color Solid at Lightness 50

The constantly changing hue and the "loops" are indicative of the difficulty inherent in using visual coordinate systems for mathematical calculations of production batch preformulation and shading. The basic difficulty is that at no two points in the visual color sphere will the addition of a single pigment have the same hue effect on the color to which it is added. To overcome this handicap with a system based upon the Modified Adams Coordinate System would require a mathematical system so complex as to render it useless for routine production use.

The Mathematical Color System

The development of a mathematical system for the preformulation and shading of blended colors on a routine production basis requires an approach to the problem which is not based upon the complexity of the visual response of the human eye. The solution of the problem can be simplified through the use of a specialized coordinate system which has little relationship to visual color coordinate systems.

This coordinate system should be developed jointly with the mathematics required for the preformulation and shading of colors. In this manner the overall system can be kept simple both in concept and in use.

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The Visual Color Solid

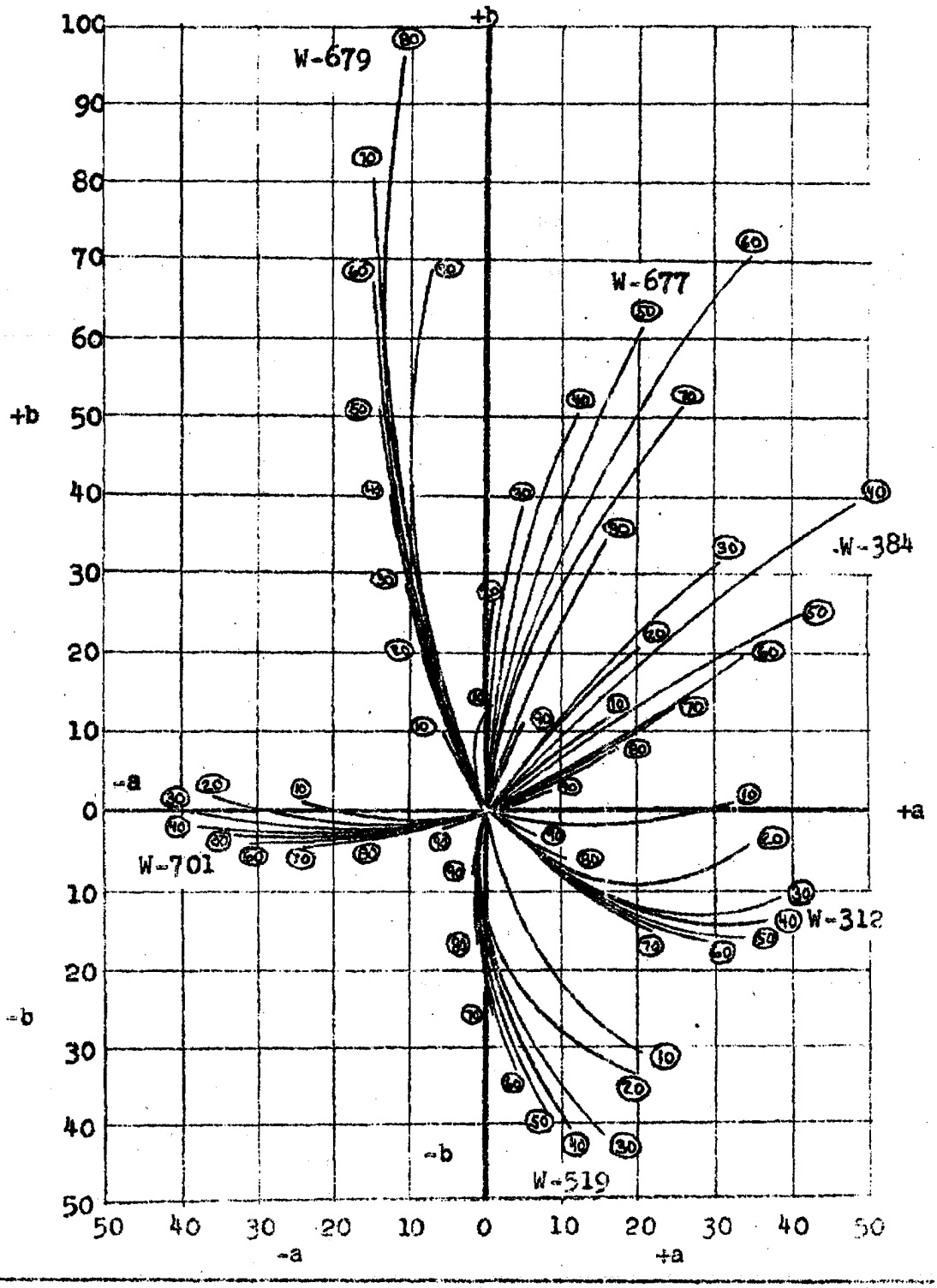
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Figure IX

VISUAL COLOR SOLID - MODIFIED ADAMS' COORDINATE SYSTEM

SATURATION AND HUE EFFECT USING SINGLE COLOR PIGMENT

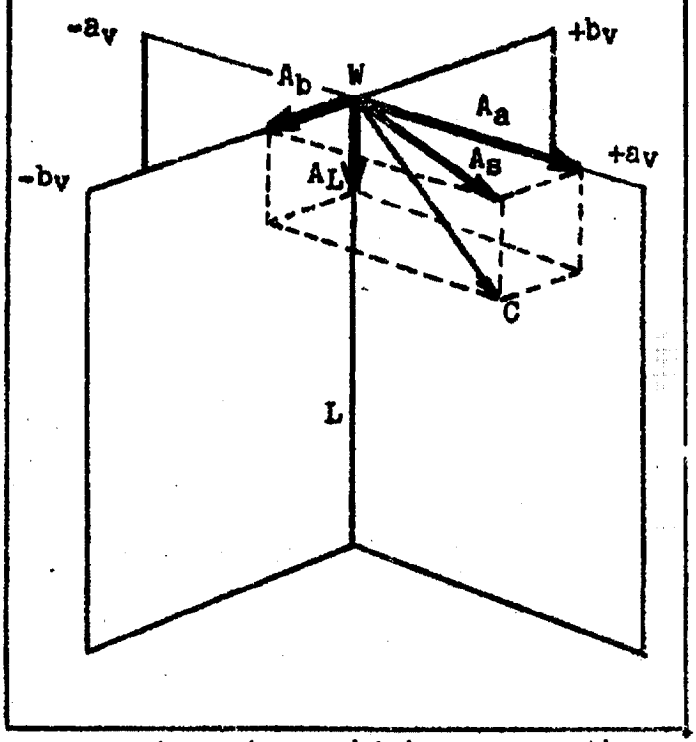
Note: (30) refers to lightness (L) value



The simplest system of three dimensional mathematics is known as "vector" mathematics. (Note Figure X.) If one part of a color pigment dispersion is added to 100 parts of neutral white dispersion, the color of the mixture will move from the color of the white (w) to the color of the blend (c). The vector (wc) represents the overall path taken during the addition of the color pigment dispersion to the white pigment dispersion. If we arbitrarily establish the blend of one part of color pigment dispersion to 100 parts of standardized neutral white dispersion as a basis for measurement, the length and direction of the (wc) vector will accurately reflect the color characteristics of the color pigment dispersion.

Figure X

"Color Characteristics" Vectors



The (wc) vector can be readily broken down into three component vectors which measure the length of the (wc) vector in terms of the three components of the rectilinear coordinate system L, a_v and b_v. These vector components, A_L, A_a and A_b are called the "color characteristics" of the color pigment dispersion. A further vector component A_s, known as the "saturation color characteristic" can be produced from the combination of the A_a and A_b vectors using the following equation:

$$A_s = (A_a^2 + A_b^2)^{1/2} \quad \ldots\ldots\ldots\ldots\ldots \quad (I\text{-}15)$$

The hue of the color pigment dispersion can be calculated from the A_a and A_b color characteristics using the following equation:

$$\text{Hue} = A_a/A_b \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (I\text{-}16)$$

If vector mathematics are to be employed in the calculation of production color preformulations and shading "hits", the first limitation must be established for the coordinate system.

(I) The mathematical hue of all combinations of a given color pigment dispersion and the neutral white pigment dispersion must be constant.

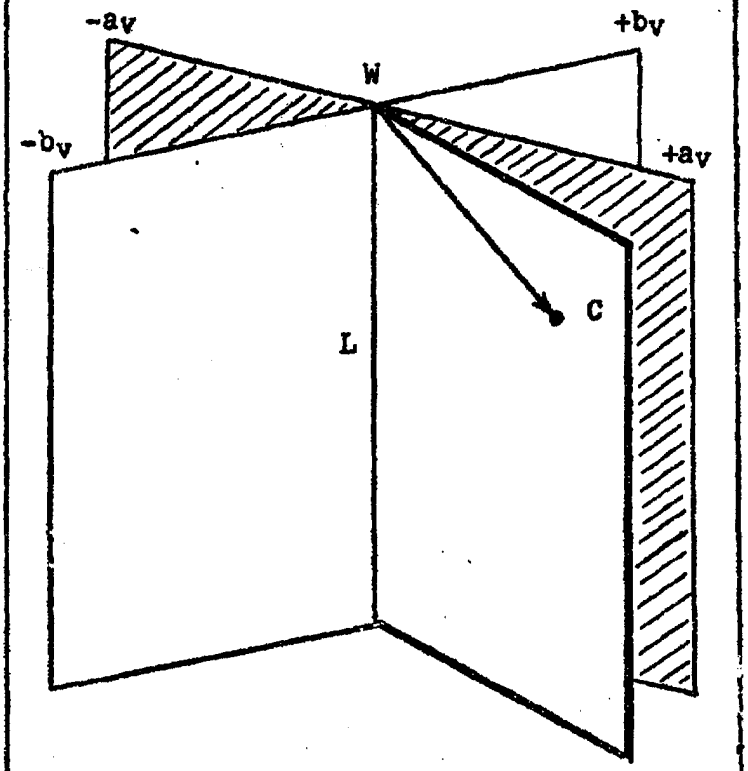
This limitation establishes the locus of all combinations of the color pigment dispersion with the neutral white pigment dispersion as a plane which incorporates the neutral or "L" axis of the color solid as one of its boundaries. (Note Figure XI.) The (wc) vector lies in this plane and serves, together with the neutral axis to define the locus of the plane.

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The magnitude and direction of the (wc) vector can be modified within the constant hue plane by the conditions under which the color pigment dispersion is used. These conditions, which are independent of the color pigment dispersion except for its masstone lightness, will independently affect the lightness component (A_L) and the saturation component (A_s or A_a and A_b). The magnitude of the saturation component (A_s) is reduced as the lightness under which it is used is reduced. (Note Figure XII.)

Figure XI

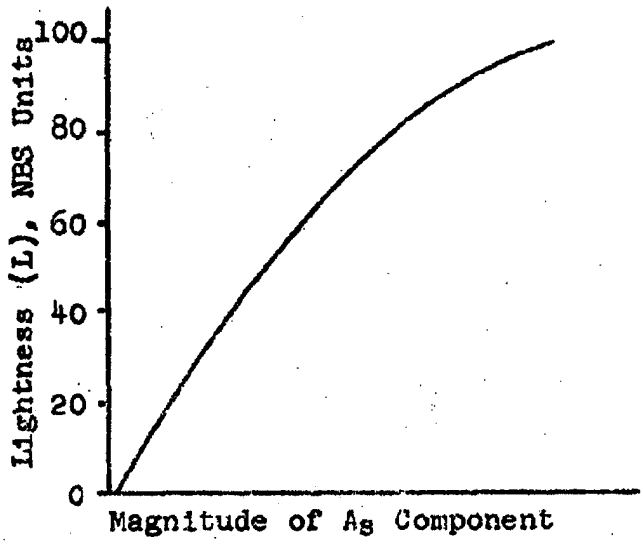
The Vectoral Coordinate System



The magnitude and direction of the lightness (A_L) vector component are controlled by the lightness conditions under which it is used and the masstone lightness of the color pigment dispersion. (Note Figure XIII.) If a given color pigment dispersion has a masstone lightness of L = 40, the use of this dispersion at lightness conditions above L-40 will result in a reduction of the lightness of the blend and a negative (A_L) vector component for the color pigment dispersion. The magnitude of this negative (A_L) component will increase as the lightness difference between L = 40 and the lightness at which the color pigment dispersion is used increases.

Figure XII

Effect of Lightness on A_s



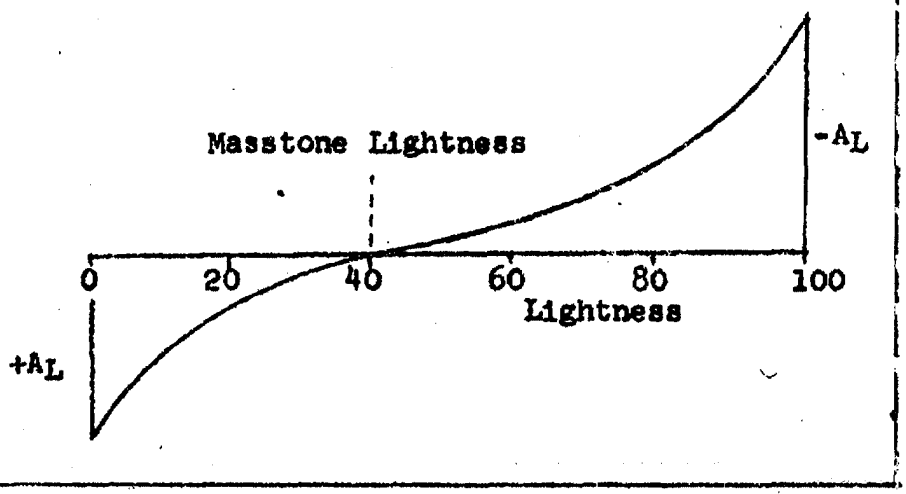
Conversely, if the color pigment dispersion is used at lightness conditions less than its masstone lightness (L-40), the effect of using this color pigment dispersion will be to increase the lightness of the blend and a positive (A_L) vector component for the color pigment dispersion. The magnitude of this positive (A_L) vector component will increase as the

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lightness difference between L=40 and the lightness at which the color pigment dispersion is used increases. Because the magnitude of the lightness (A_L) and saturation (A_s) vector components of the color pigment dispersion are affected by the lightness conditions under which it is used, it is necessary to evaluate (A_L) and (A_s) at standard conditions, which were arbitrarily selected as L = 95.7, the masstone lightness of the testing white.

Figure XIII

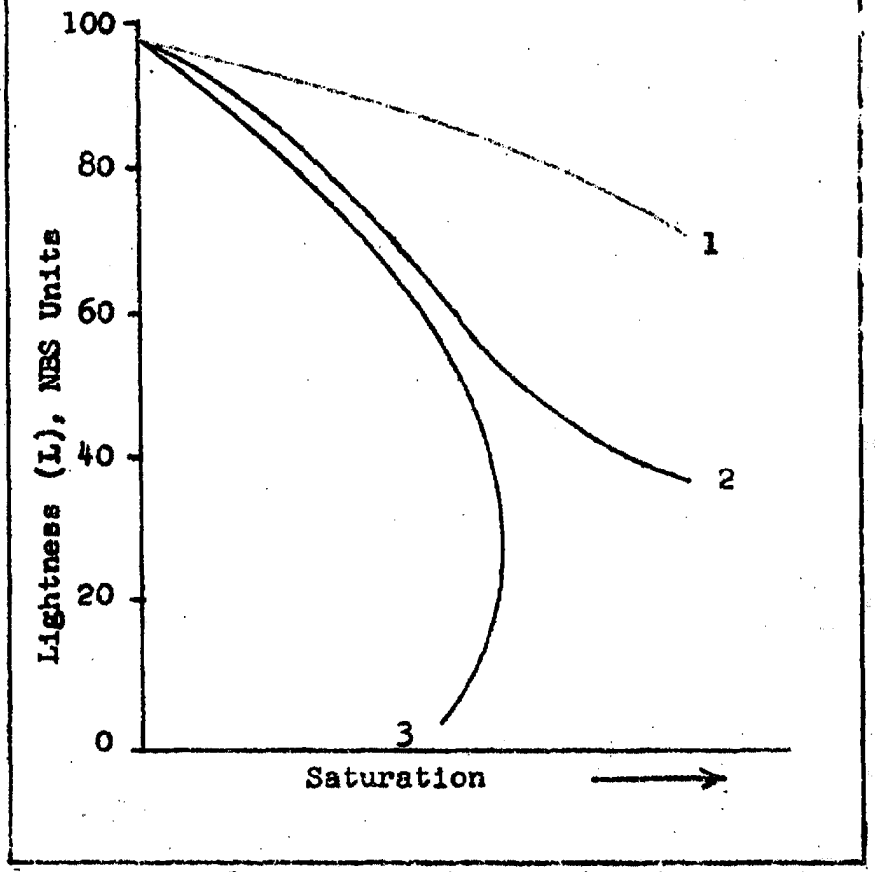
Effect of Lightness and Masstone Lightness on A_L



Since the magnitude of the lightness (A_L) and saturation (A_s or A_a and A_b) vector components are independently affected by the conditions of use, it is not surprising that the shape of the saturation vs. lightness path resulting from the addition of a color pigment dispersion to a neutral white pigment dispersion is a curved line in the constant mathematical hue plane of the desired Vectoral Coordinate System. Each color pigment dispersion has its own characteristic curve, but three general curve shapes have been noted to date. Curve (1) is typical of very light color pigment dispersions such as chrome yellow. Curve (2) is typical of saturated color pigment dispersions intermediate in lightness such as the cadmium reds. Curve (3) is typical of fine particle size color pigment dispersions, which because of their fine particle size are relatively dark, such as phthalocyanine or "Monastral"* Blue. (Note Figure XIV.)

Figure XIV

Typical Shapes of Saturation vs. Lightness Curves

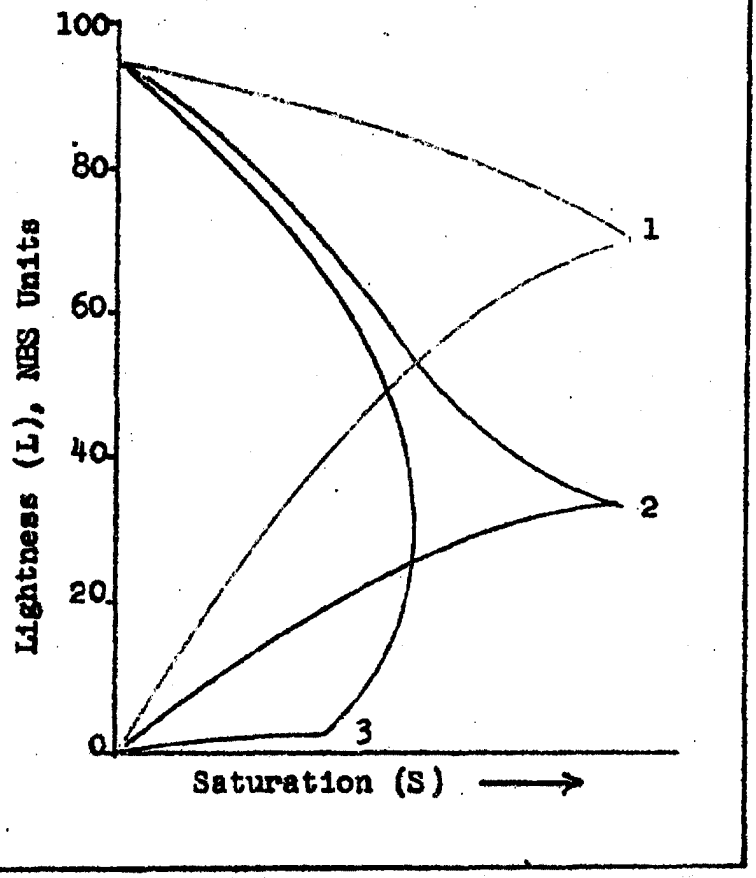


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These color/white lightness vs. saturation curves are unique in that they serve to define the maximum saturation obtainable with the given color pigment dispersion. This relationship is of particular importance in the evaluation of new pigments and the formulation, preformulation and shading of colors. However, these curves, because they are only made up of a color pigment dispersion and a white pigment dispersion terminate at the masstone lightness of the color pigment dispersion. It is possible to extend these curves through a hypothetical mathematical mixture of the color pigment dispersion with a hypothetical neutral black of the same strength as the neutral white. This would result in the curves shown in Figure XV which are the curves of Figure XIV plus the hypothetical color pigment dispersion/neutral black curve. These curves are the complete maximum saturation curve.

Figure XV

Typical Maximum Saturation Curve



These color/white, color/black maximum saturation curves are only valid at the specific hue of the color pigment dispersion. The color pigment dispersion can often be used in conjunction with other, more saturated pigment dispersions to produce a more saturated color than is indicated by the maximum saturation curve. To understand how this more saturated color can be achieved, it is necessary to look at the basic mechanics of color formulation.

Color Formulation and Preformulation

One of the basic problems inherent in the manufacture of pigmented finishes is the formulation of new colors as offerings to the customer or as counter-offerings to competitors' color offerings to the customer. The problem is further complicated, from the production point of view, by the fact that many of the formulations approved by the customer are not designed for the rapid and economical production of the color. A portion of this difficulty is caused by a trial-and-error approach to color formulation problems without proper regard to the fundamentals of color formulation. The remainder of the difficulty results from the need to match competitor developed colors on a non-metameric basis, thus extending into our production operations, due to the need to match pigmentation, any fundamental errors of color formulation made by the competitors' formulating group.

From a production viewpoint, these troublesome color formulations fall into one or more of three categories:

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1. The formulations contain too few pigments to allow the shader to compensate for the normal lot to lot variation in the pigmented intermediates.

2. The formulations contain extraneous pigments which are not justifiable by cost or durability considerations. The presence of these pigments unduly complicates the shader's job and results in more shading "hits" per batch than should be necessary to match the color.

3. The formulations contain sufficient pigments to allow the shader to compensate for the normal lot to lot variation in the pigmented intermediates, but the choice of the pigments is such that the shading function is complicated and results in extra shading "hits" per batch.

The fundamentals of color formulation are relatively simple, if the limiting conditions of durability and cost are disregarded. Color is three-dimensional in concept and therefore the satisfactory production of the color on a reproducible basis requires sufficient latitude in the formulation to allow the producing plant to compensate for the inherent lot to lot variation in the lightness, hue and saturation of the component colorants.

The most rudimentary type of color formulation is required for the production of opaque, non-metallic or "solid" colors. These colors can be satisfactorily formulated using two color pigment dispersions plus a white and black. Formulation on this basis provides the necessary three degrees of freedom required for the adjustment of the formulation for lightness, hue and saturation variation of the component colorants.

The mechanics of formulating a green color (C) are most readily understood when expressed in terms of the Vectoral Coordinate System. (Note Figure XVI.) Assume that color pigment dispersions (C_1) and (C_2) have been selected for formulating (C), either through a colorimetric evaluation or through the proper use of the formulating tables.

Color (C) has a lightness of $L = L_s$. At this lightness level, the maximum saturation curve for colorant (C_1) has a white/colorant (C_1) composition (C'_1) and the maximum saturation curve for colorant (C_2) has a white/colorant (C_2) composition of (C'_2). If the white/colorant compositions (C'_1) and (C'_2) are added together in the right proportions, the hue of the desired color (C) will be matched at point (C'_3). Since (C'_3) is further from the neutral gray axis than the desired color (C), it is more saturated. The saturation is then reduced through the use of the proper amount of a white/black combination of lightness (L_s) to move the color blend from (C'_3) to (C).

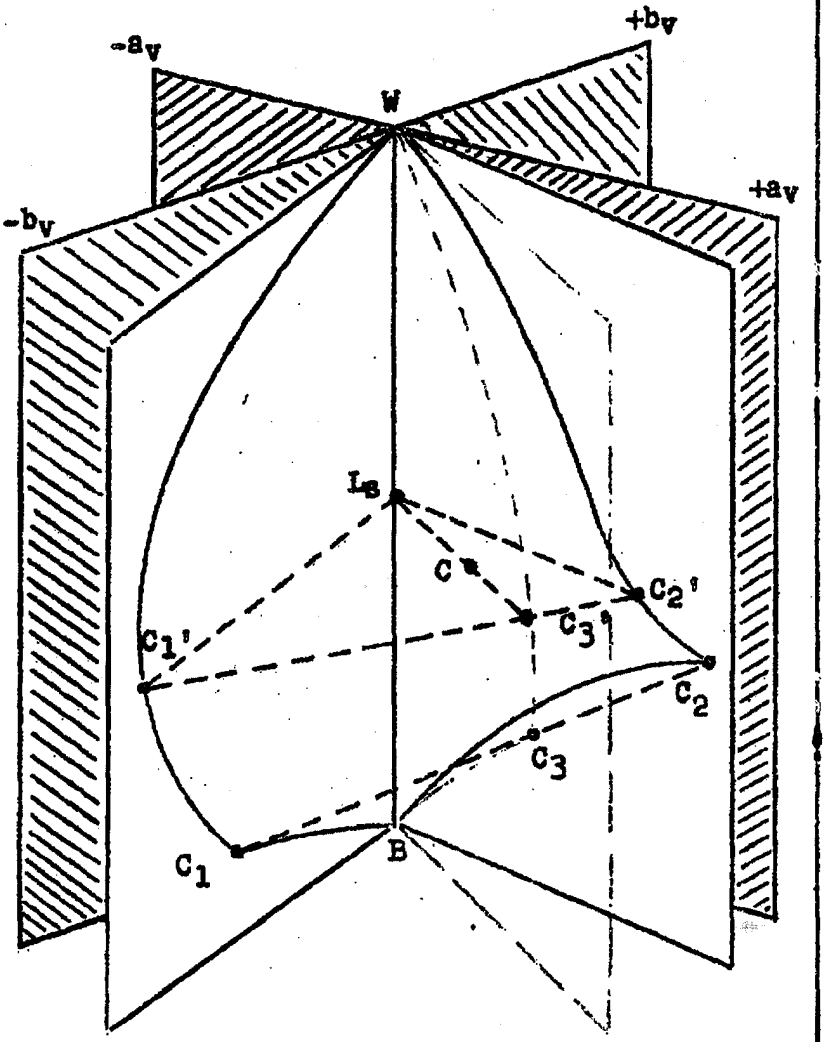
The Mathematical Color System is particularly adept at handling this type of formulation problem and is designed to do so on a production basis to compensate for the lot to lot variation in the color characteristics of the colorants used. It will be recalled that the color characteristics of each colorant are characterized by the vector components (A_L), (A_a), (A_b) and the masstone lightness of the colorant (L'). When combinations of more than one colorant are

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used, these combinations are characterized by the sum of the vector components of each colorant, multiplied by the percentage of the colorant in the blend. Conversely, if the hue (a_v/b_v) of the desired color is known, the proportion of the two colorants necessary to determine the hue can be calculated. Under the Mathematical Color System, there are three steps necessary to match the desired color (C).

Figure XVI

Solid Color Formulation



1) Determine the ratio of colorants (C_1) and (C_2) necessary to match the hue of the desired color (C). Calculate the saturation (A_s) and lightness (A_L) characteristics of this blend.

2) Determine the amount of the colorant blend which should be added to white to obtain the lightness of the desired color.(L_s). Calculate the saturation (S) of the white/colorant blend (C'_3).

3) Determine the amount of neutral gray of the lightness (L_s) of the desired color (C) necessary to reduce the saturation by the distance (C_3- C).

Under this system, the color formulation can be readily computed and would be the sum of the white, black and colorants (C_1)and(C_2)used in steps (2) and (3). In actual practice, of course, the black and white dispersions used in color formulation are rarely neutral. In the Mathematical Color System, minor corrections in the value of the vector components A_L, A_a and A_b are made prior to step (1) to compensate for the hue and saturation of the specific black and white used in the color formulation.

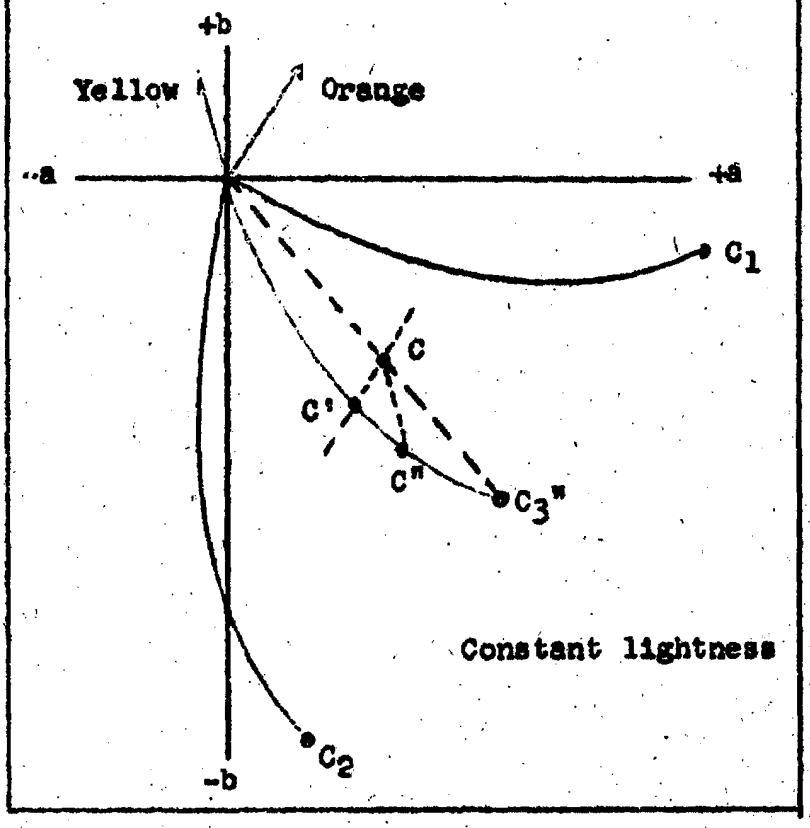
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It must be remembered that the formulators are matching these colors through the use of visual color perception. Under these conditions, they do not have the inherent simplicity of the Mathematical Color System or the Vectoral Coordinate System to guide them but must cope with the complexity of the visual response of the human eye (note discussion of the Modified Adams Coordinate System). Under the visual system, it is possible for extraneous pigments to appear in the overall formulation.

Consider the formulation of Figure XVI. If the color is formulated on a visual basis, point (C''_3), which is now of the same visual hue as the desired color (C'), actually contains a higher ratio of (C_2) to (C_1) than is necessary. (Note Figure XVII which represents a diagram of the color solid at the lightness of the color to be matched.) The addition of neutral gray does not move the color from (C''_3) to (C), because of the non-linear visual effect. The color instead moves from (C''_3) to (C') or (C") depending on the amount of neutral gray added to reduce the excess saturation of (C''_3). The proper adjustment from (C") or (C') to (C) is achieved through increasing the ratio of colorant (C_1) to colorant (C_2) in the formulation.

Figure XVII

Difficulty of Visual Color Formulation



However, visual evaluation of the color difference often results in the addition of an additional pigment rather than the readjustment of the formulation within the confines of the existing colorant makeup. For example, in Figure XVII, point C will visually appear to be more orange than point C', thus leading many formulators into the "extraneous pigment" trap by inducing them to add a small amount of orange pigment dispersion to correct the color from (C') to the desired color (C). Similarly, since the desired color (C) is visually more yellow than point (C"), the formulator may add a yellow to adjust from color (C") to the desired color (C).

The ideal color, as was mentioned earlier, contains four colorants; namely, white, black, colorant (C_1) and colorant (C_2). This arrangement gives the production shader three degrees of freedom (i.e., he can change the proportion of any or all of three colorants in relation to the fourth) with which to match a three-dimensional color. The addition of the extraneous colorant (orange or yellow) complicates rather than simplifies his task. The additional colorant must be used in many cases to obviate the possibility of a metameric color match. This means that the shader must preformulate a color

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match which, if the orange is excluded, must lie somewhere away from the color standard (C) along line (C) (C'). In general, the use of an extraneous pigment in a production formula results in the use of more preformulation and shading time per batch.

The formulation of "high flash" Finishes containing aluminum flake (metallic colors) is somewhat more complex both in concept and in operation, than the formulation of solid colors. This increased complexity results from the addition of a further color dimension ("two-tone") to the basic lightness, hue and saturation requirements of solid color technology. As a result, the formulator must have four degrees of freedom in his formulation or the proper combination of a minimum of five pigments: white, black, aluminum, and two colorants, (C_1) and (C_2). Historically, metallic colors have also used two additional colorants which, when combined, were opposite in hue to the desired color and were used instead of the black to reduce saturation (complementary color matching). This technique, while theoretically feasible, had many practical limitations for it forced the formulator and the production shader to cope with the problem of matching, under the limitation of visual conditions, not only the hue of the desired color but also the reverse, or complimentary, hue of the color. The technique, under visual conditions, inherently requires more preformulation and shading effort than the more conventional five-pigment system and has therefore been largely discontinued.

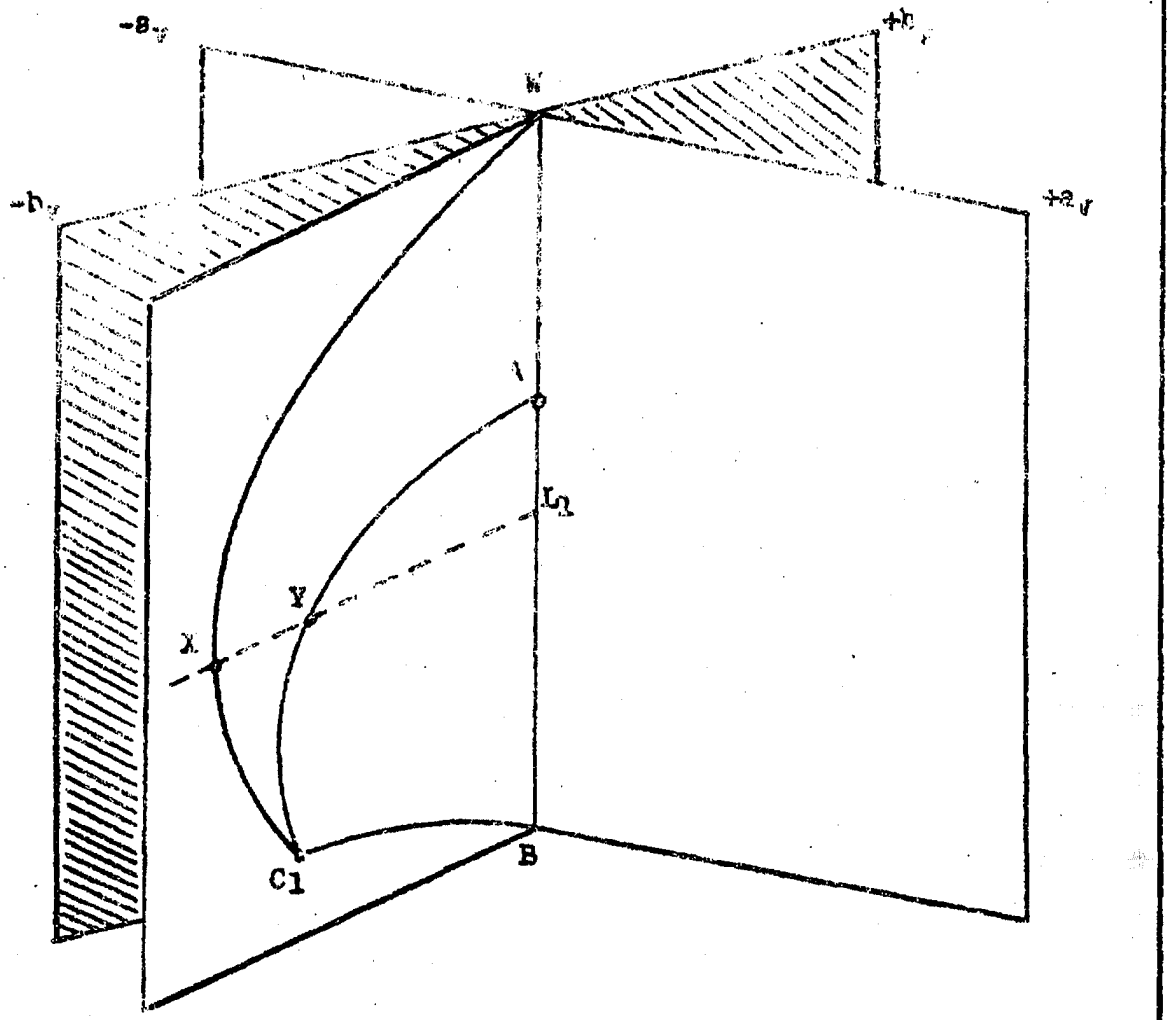
To understand the concepts inherent in the formulation, preformulation and shading of "metallic" finishes, it is necessary to consider them from the viewpoint of the Mathematical Color System and the Vectoral Coordinate System. (Note Figure XVIII.) Again, for purposes of simplicity, it is assumed that the white, aluminum and black are neutral. If colorant (C_1) is mixed in varying proportions with the neutral white and also with neutral black, the resulting curve (W) (C_1) (B) represents the saturation limit acheivable with colorant (C_1), the white (W), and the black (B). A similar mixture of colorant (C_1) with the aluminum (A) will result in curve (A) (C_1) (B) which represents the saturation limit of aluminum (A)/colorant (C_1) blends. In reality, this means that for formulating purposes there are TWO COLOR SOLIDS - METALLIC AND NON-METALLIC. All metallic colors containing colorant (C_1) must be formulated in the (A) (C_1) (B) color range. Examination of Figure XVIII will indicate that the metallic color solid will always be less saturated than the solid or non-metallic color solid until the point (C_1) is reached, representing the masstone lightnsss of 100% colorant (C_1).

The explanation for this reduced saturation can be made by means of the Mathematical Color System. If the "two-tone" qualities of the aluminum are ignored, for the moment, the aluminum can be considered as a neutral gray composed of a fixed combination of neutral white and neutral black and having the same strength as the neutral white. The presence of this black in the formulation at any lightness (L_1) will reduce the saturation which would otherwise be obtained with the colorant (C_1). It does so by reducing the proportion of color in the formulation. For example, since the white (W) is lighter than the neutral gray (aluminum) (A), it will take more of colorant (C_1) to change the color of 100 units of white (W) to a given lightness (L_1), or point (X), than it will to change the color of 100 units of neutral gray (A) of the same strength as the white to the desired lightness (Y). Under the concept of the Mathematical Color System, only color pigment dispersions have a saturation vector component (A_s). The saturation

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Figure XVIII

Solid And Metallic Color Solids



of the color/white or color/gray blend is a function of the amount of color in the color blend. Since the color/white blend has more of colorant (C_1), it follows that it must be more saturated than the color/gray blend at the same lightness (L_1).

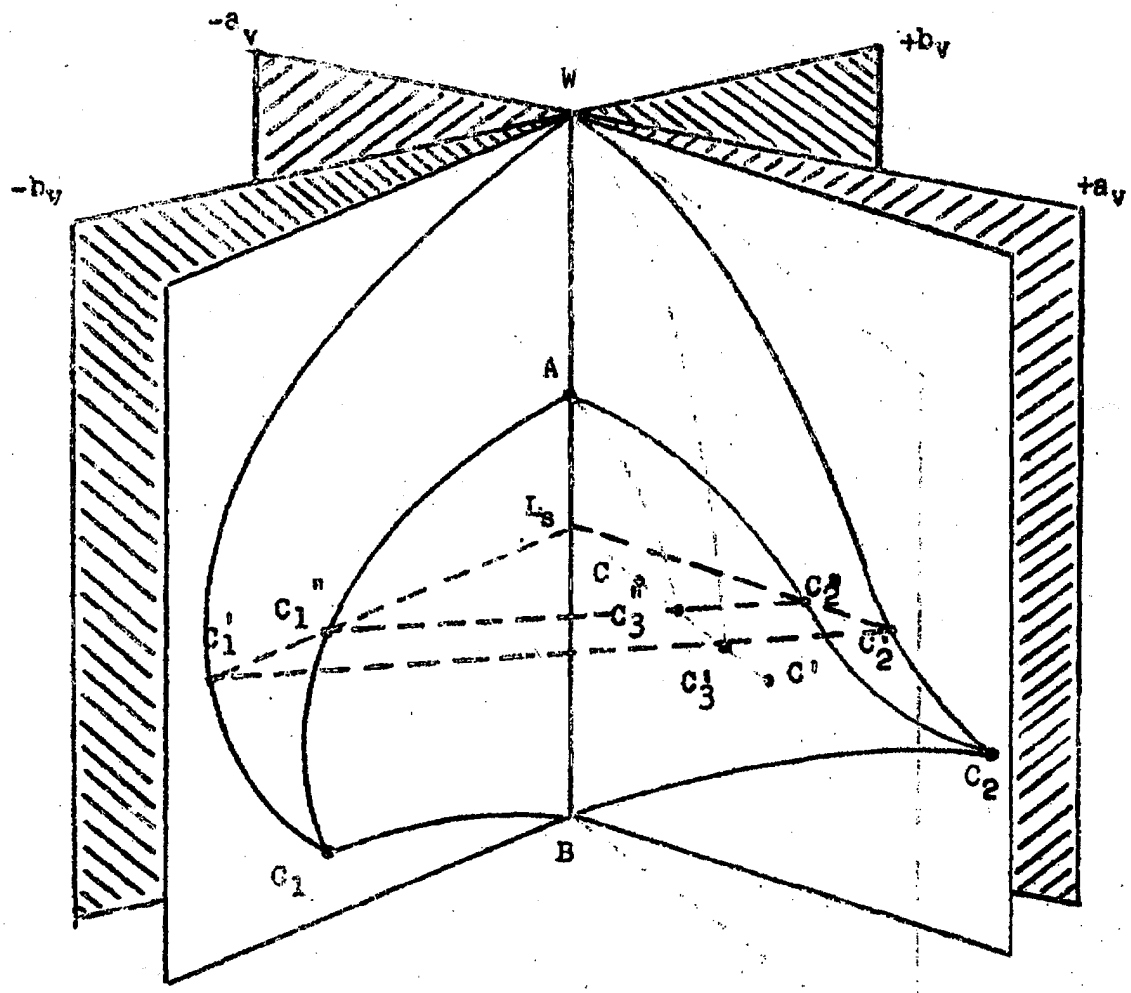
In the preceding discussion, it was assumed that the aluminum colorant was of the same tinting strength as the neutral white. This assumption was made for purposes of clarity. However, the reduced saturation effect is valid regardless of the strength differences because the basic maximum saturation curve for given color/white or color/aluminum combinations will remain the same regardless of the strength of either component. The only change resulting from modifying the strength of a given component is in the ratio of the color to white or the color to aluminum required to match a given point on a curve. Since the strength of a pigment dispersion is dependent upon the degree of dispersion, these varying formulations will provide the same ratio of dispersed color pigment to dispersed neutral pigment regardless of any difference in strength of the components.

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The theoretical techniques followed in matching metallic colors are basically similar to those used in matching the solid color. Assume that color (C) of Figure XIX (Page I-23) is to be formulated from the same color pigment dispersions, (C_1) and (C_2), white (W), black (B) and aluminum (A). The fundamental approach to this problem requires the formulation of two color blends to the lightness, hue and saturation of the desired color (C). The first color formulation is the solid color composed of white (W), black (B) and colorants (C_1) and (C_2). White/colorant concentrations (C_1') and (C_2'), corresponding to the lightness (L_s) of the desired color (C) are blended in the proper ratio to match the hue (C_3') of the desired color (C). A black/white blend of the same lightness (L_s) as the desired color (C) is added to blend (C'_3) in sufficient quantity to move color (C_3') to the standard (C). This solid color formulation is based on white and contains no aluminum. The solid color will have only limited "two-tone" characteristics because the white pigment scatters the light, adversely affecting "two-tone".

Figure XIX

Metallic Color Formulation



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The second color formulation is based upon aluminum, black and the two colorants (C_1) and (C_2). In this case, aluminum/colorant combinations (C_1") and (C_2"), corresponding to the lightness (L_s) of the desired color (C) are blended in the proper ratio to match the hue (C_3") of the desired color (C). An aluminum/black blend of the same lightness (L_s) as the color standard (C) is added in sufficient quantity to move color (C_3") to the standard (C). This metallic color contains no white, and therefore has the maximum "two-tone" characteristics possible in the formulation. If color (C) has greater "two-tone" characteristics than the aluminum, black, colorant (C_1) and colorant (C_2) combination necessary to match the lightness, hue and saturation, the wrong colorants or the wrong aluminum were chosen to match the color.

There are now two formulations for color (C), one, the solid color formulation, having less "two-tone" than the desired color and the other, the completely metallic formulation, having a greater "two-tone" than the desired color. Since both of these colors match the desired color (C) for lightness, hue and saturation, the color can be completely matched through the simple combination of the two formulations in the right proportion to give the proper "two-tone".

The Mathematical Color System technique for formulating metallic colors follows the same technique, in that the solid color and completely metallic color formulations are mathematically computed using the previously discussed technique of matching the hue first, followed by the lightness and the saturation and then mathematically combined in the proper ratio to give the desired "two-tone".

The current method of formulating or preformulating metallic colors does not use the two-formulation basis, because it is virtually impossible to visually formulate a solid color which will match a metallic formulation on a visual basis. The technique involved in most visual formulation or preformulation of metallic colors results in the formulation of the metallic color without white and to a slightly lower lightness than the standard and then the use of small amounts of white to reduce the "two-tone" to the desired level. While reducing the "two-tone" value, the white will also raise the lightness of the blend to that of the desired standard, presuming that the lightness difference was commensurate with the required reduction in "two-tone". Visual formulation of metallic colors suffers from the same inherent difficulties which plague solid color formulation with the added complication of a "two-tone" color match.

There is one further consideration which has not been explored. Consider again the locus of the desired color in Figure XIX. If the desired color was at (C') instead of (C), it would be impossible to match it with the colorants (C_1) and (C_2) because the maximum saturation (C_3') obtainable with the white/colorant (C_1) and (C_2) blend is less saturated than the desired color. A similar situation exists for the maximum saturation of the metallic blend (C_3"). This situation requires the selection of other colorants, since it is impossible to increase the saturation of color blends (C_3') and (C_3") without the use of additional, more saturated colorants.

While the use of two color pigment dispersions plus black, white and, in the case of metallic colors, aluminum, is recommended for the formulation of colors, there are certain areas where one color pigment dispersion and, in some cases, black can be excluded from the

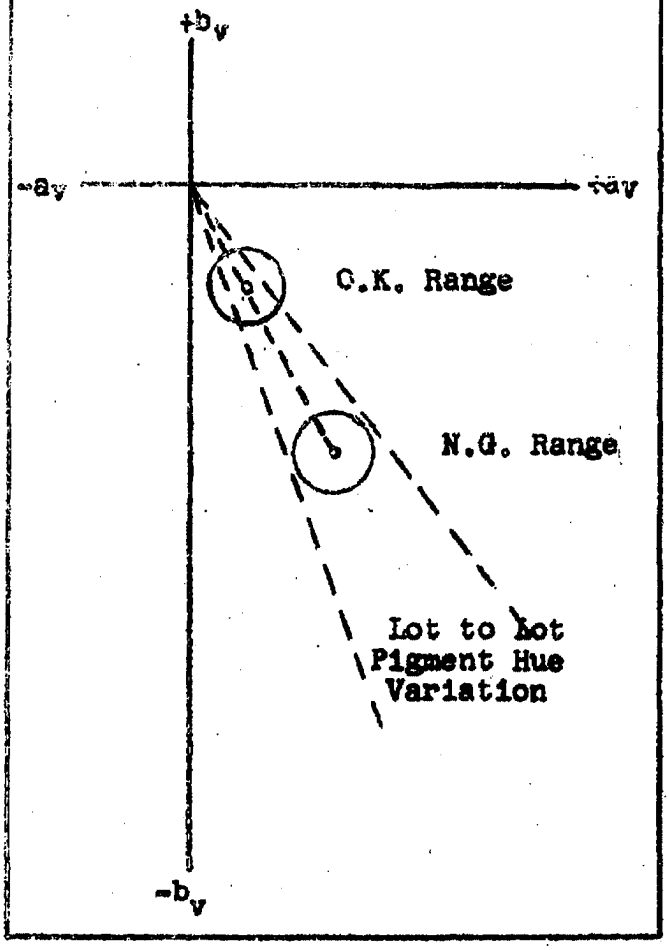
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formulation. This formulation area is the essentially neutral area where the lot to lot variation in the color of the single color pigment dispersion used is effectively diminished by the proximity of the desired color to the starting white, gray or aluminum which constitutes most of the formulation.

In Figure XX the basis for such a formulation is shown on a plane of constant lightness.

Figure XX

Single Color Pigment Formulations



Since these formulations do not contain the required number of colorants to provide the three degrees of freedom required to adequately control the shading and production of such a color formulation, the success of the formulation is based upon three limitations, each of which must be met.

1) The starting white, aluminum, or gray which constitutes the bulk of the formulation, must be inherently reproducible on a production basis in lightness, hue and saturation. Any lot to lot shift in the color of the white, aliminum or gray will increase the probability of a poor color match which cannot be shaded within the composition confines of the color formulation.

2) The colorant used to tint the starting color must be reproducible enough in production to allow its use in this type of formulation.

3) The magnitude of the "commercial color tolerance" for such a color must be adequate to absorb the sum of the color variation of the starting color and variation of the color pigment base used for tinting the starting color.

Typical formulations of this type are found in the field of "high bake whites" and in certain Automotive neutral metallic finishes. The use of such formulations should not be encouraged because of the lack of a sufficient number of colorants to allow adjustment of the formulation for large lightness, hue and saturation changes in any of the components.

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Shading of Production Colors

The routine production of a color formulation which has been accepted by a customer is the main objective of the Finishes industry. The production of this color on a routine basis depends upon the ability of the production organization to cope with the lot to lot variability inherent in the manufacture of the pigmented bases which are blended to produce the desired color. The conversion from a laboratory formulation to an O.K. production batch requires two operations in the field of color.

1) The reformulation of the color with the specific lots of colorant currently in use by the plant. This operation, known as "preformulation", is basically similar to the formulation process. The preformulation operation is more simplified since the required pigment dispersions and the approximate formulation have already been established. The "preformulation" usually is considered complete when an approximate match has been obtained with respect to the color standard.

2) The second step consists of the adjustment of the color of the blended batch to that of the standard. This step is known as "shading" and involves a minor manipulation of the colorant blend to bring the color of the batch within a given "commercial color tolerance" of the standard.

These operations are carried out on a plant level by highly trained personnel, known as "shaders", using a combination of visual color perception and experience. Shading, as currently practiced, is an art, and has several limitations which combine to restrict the productive capacity of any plant to the efficiency of its shaders in obtaining a satisfactory color match.

This shading efficiency is controlled by the inherent limitations of visual color perception. A new color is usually a problem in production until the shader has built up a visual experience which allows him to estimate the type and amount of color necessary to adjust a given color difference. Batches which fall outside the scope of this color experience usually baffle the shader and require days or even weeks of color adjustment. The training of new shaders requires an extensive "apprenticeship" period before they achieve sufficient proficiency to "ply their trade".

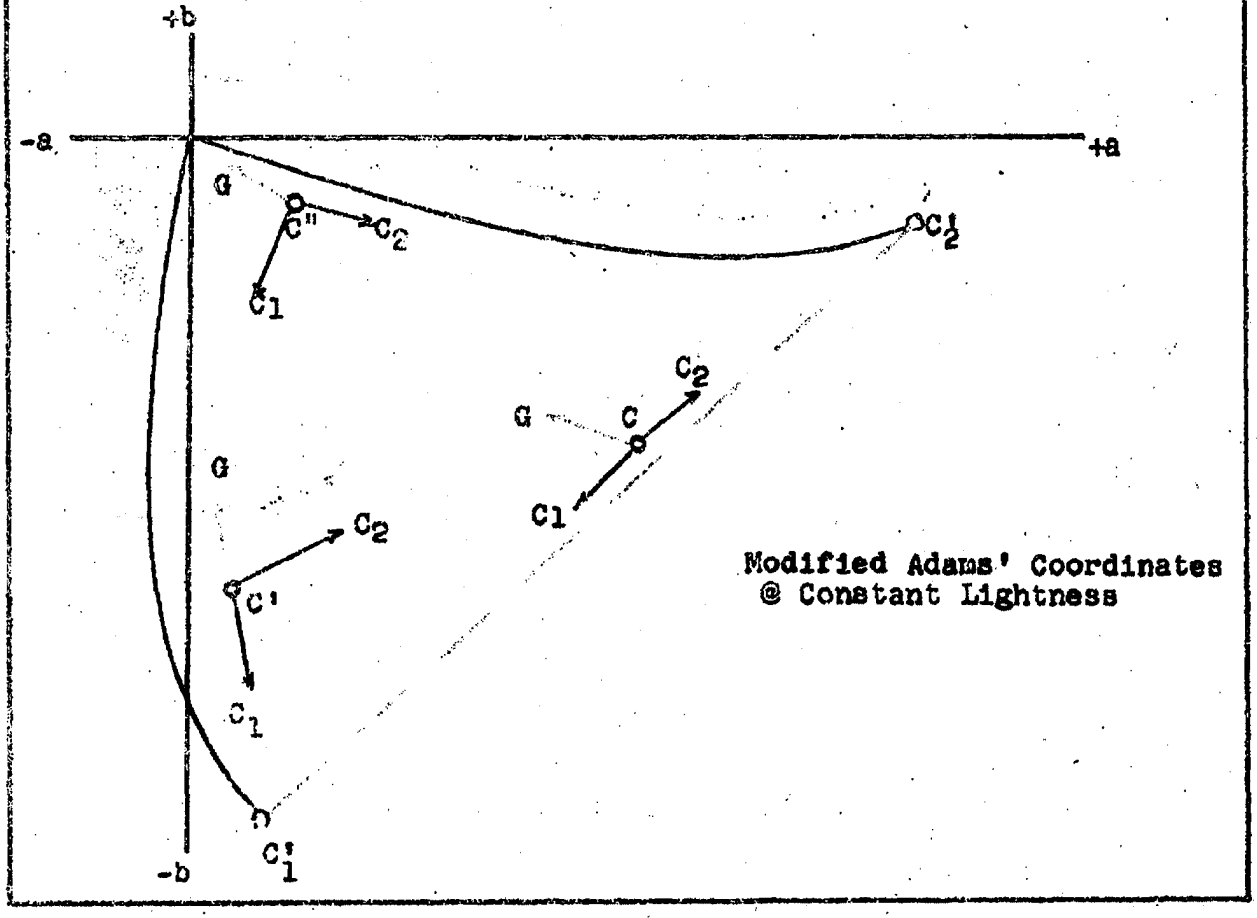
These difficulties may be traced to the non-linear color response of the eye and its lack of ability to measure in the absolute terms of lightness, hue and saturation the color difference existing between the batch and the standard. It is difficult for a person to conceive that the addition of a colorant results in a change in color in all three color directions and that the direction and magnitude of the color change is dependent on the lightness, hue, and saturation of the batch.

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For example, let us examine the effect of adding either colorant (C_1) or colorant (C_2) to three colors (C), (C') and (C") of the same lightness. Figure XXI represents this color effect in terms of the visual coordinate system. Curve ($X\text{-}C_1'$) is the locus of combinations of neutral gray of lightness (L_1) and a white/colorant (C_1) combination of lightness (L_1). Curve ($X\ C_2'$) represents the locus of combinations of the neutral gray with the white/colorant (C_2) combination of lightness (L_1). The colorants (C_1) and (C_2) are both darker than lightness (L_1). The addition of colorant (C_1) will result in a color movement in the direction of (C C_1), (C'C_1) and (C"C_1) as shown by the blue arrows. In addition, the use of colorant (C_1) will result in a reduction of the lightness of color blends (C), (C') and (C"). The addition of colorant (C_2) will result in a color movement in the direction of (C C_2), (C'C_2) and (C"C_2) as shown by the red arrows. The use of colorant (C_2) will result in a reduction of the lightness of the color blends (C) (C') and (C"). The use of neutral gray will not affect the lightness of the color blends, but will affect the color as shown by the green arrows (C G), (C'G) and (C"G). A properly trained shader not only has to be aware of the differences in these color directions but he also must be aware of the magnitude of the color movement which will be induced in a given batch by this color "hit". Since the composition of this "hit" results from the combination of the shader's visual impression and his visual experience, it is apparent that any shading system based on visual techniques will result in a high frequency of erroneous "hits".

Figure XXI

Typical Color Addition Effects



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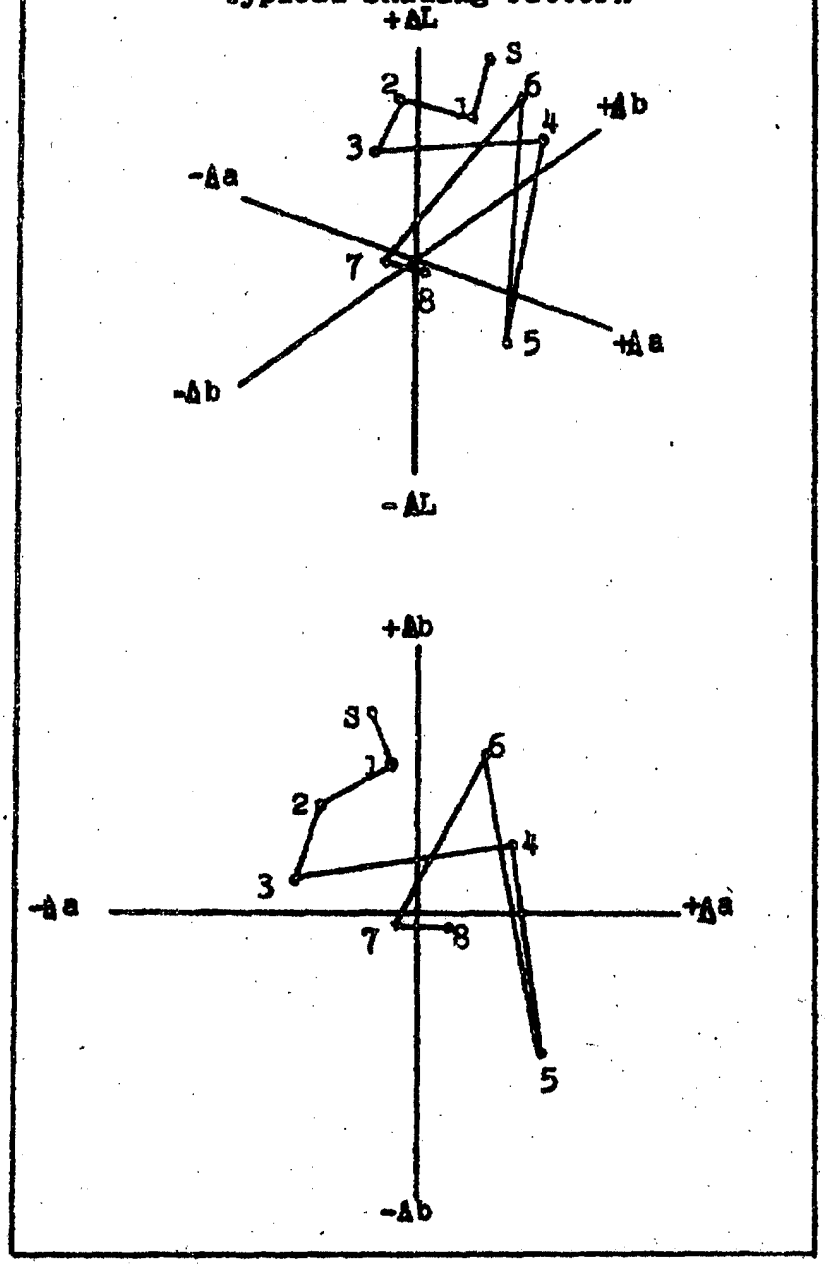
Colorimetric evaluation of routine batch shading histories bears this out. The effect of the shading "hit" may be in almost any direction. Figure XXII presents a typical shading history of eight shading "hits". Notice that of the eight "hits" only two (S-1) and (6-7) were approximately in the right direction, while five were, to a lesser or greater degree, away from the desired color.

Examination of many of these records indicates one thing. The bulk of shading effort is devoted to aimless wandering until one random shading "hit" corrects for the bulk of the color difference. In the case of our example, the seventh "hit", which moved the color from point (6) to point (7), was the key to shading the batch. This principle seems to hold for a high percentage of the batches examined and indicates that the main difference between a "good" shader and a "poor" shader is that the "good" shader comes up with this "key" color correction sooner than the "poor" shader. It should be emphasized that these "hits" were not necessarily all made to the production batch. In some cases, the "hits" were made to a sample, and rejected by the shader before they were added to the batch. However, they were included in the evaluation because they formed a part of the deductive reasoning and the shading effort which goes into the batch.

There are two possible methods for obtaining an improvement in the shading performance. Each of these methods involves the use of the colorimeter to replace the eye in the assessment of the color difference.

Figure XXII

Typical Shading Pattern



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At this point the two methods differ widely. The first method uses the colorimeter, the color difference computer, the "two-tone" meter (metallic colors only) and a special chart to allow the proper color adjustment to be made on the first attempt. The second uses the principles of the Mathematical Color System to calculate the shading "hit".

The Colorimeter-Chart Color Adjustment System

The discussion of Figure XXI emphasized the fact that the same colorant reacts in a color direction which depends upon the location of the batch in color space. This reaction obeys certain fundamental principles which, if understood, can make a shader out of a relatively inexperienced man because of the substitution of reasoning for visual experience. It is possible to go one step further and simplify the technique to the point where it is readily applicable to the routine production shading of batches.

This improved technique uses a prepared chart (note Figure XXIII) called the "color effect chart", on which the reaction of each of the formula colorants on the standard color is plotted. For example, if a "Dulux"* color (i.e., 701-60756) is composed of tinting bases such as white (743-5043), black (42-224), yellow (743-630) and red (743-895), the control chart may be prepared by using either a sample of the standard or a sample of a previously acceptable batch, adding each of the colorants individually to separate samples of the wet standard or the previously accepted batch and measuring the colorimetric effect attributable to each colorant in terms of its ΔL, Δa, Δb effect. This color difference is then plotted on the Δa Δb, ΔL Δb and ΔL Δa plots as the distance from the origin to the ΔL, Δa, Δb effect. The reverse effect is also plotted since it is equivalent, for all practical purposes, to the color effect obtained if the same quantity of colorant was removed from the batch. These lines are readily plotted on each of the three diagrams (Δa Δb, ΔL Δa, ΔL Δb) to provide the required three dimensional analysis.

This system makes use of the fact that the visual color coordinate systems, such as the Modified Adams' Coordinate System, despite their overall non-linear characteristics, are virtually linear over the short distances usually encountered in production color shading.

The use of the system is relatively simple. Assume that color (C) has been charged to the mixer. A sample is sprayed (or cast) and the resulting color is measured vs. the standard panel. The color difference existing between color (C) and the standard is computed in terms of ΔL, Δa and Δb and the results plotted on the color effect chart. (Note Figure XXIV.) The procedure from this point is identical for all colors.

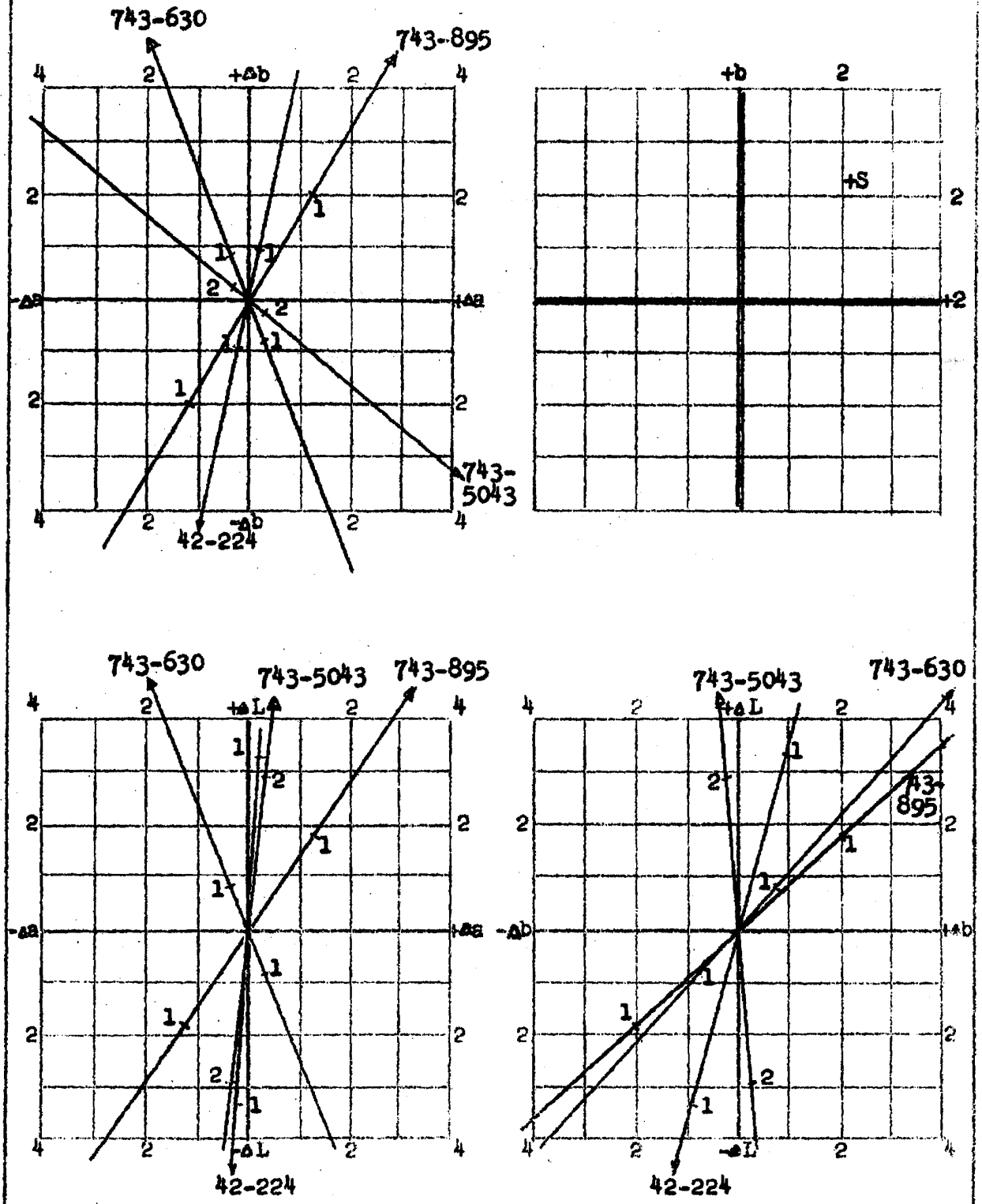
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Figure XXIII

Colorimeter-Chart Color Adjustment System

Master Color Effect Chart



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Step 1 - Inspect the $\Delta L\ \Delta a$, $\Delta L\ \Delta b$ and $\Delta a\ \Delta b$ plots. Choose a color vector (A) leading from the batch that will intersect another color vector leading toward the origin in at least two different plots. This is the second color (B) used in adjusting the batch. In Figure XXIV the 743-895 vector was used because it intersects the 42-224 vector in both the $\Delta L\ \Delta a$ and $\Delta a\ \Delta b$ plots.

Step 2 - Draw vectors corresponding to colorant (A) addition in $\Delta L\ \Delta a$, $\Delta L\ \Delta b$ and $\Delta a\ \Delta b$ plots. Extend vector until intersection with color vector(B) is obtained.

Step 3 - Label the first intercept of the drawn colorant (A) vector with the colorant (B) vector (1m). The second intercept (in different plot) will be (1x). Transpose these points to all three plots.

Step 4 - Draw lines parallel to colorant vector B from (1m) and (1x) in all three plots. Using the plot which has not previously been used to determine either point (1m) or (1x), the line from (1m) and/or (1x) will intersect with the third colorant (C). The intersection of the (1m)-vector B line with vector C is point (2m). The intersection of the (1x)-vector B line with vector C is point (2x).

Step 5 - Transpose points (2m) and (2x) to the other plots. Draw a line from (2m) to (2x). The intersection of the line with the colorant C vector is Point I.

Step 6 - Draw a line from Point I parallel to and in the reverse direction of the color vector B back to the color vector A leading from batch. This is Point II.

Step 7 - All the above Points I and II and batch are identical in each of the three color plots. The colorant add is:

Vector A from batch to Point II
Vector B from Point II to Point I
Vector C from Point I to origin

Step 8 - Measure the amount of Colorants A, B and C required to adjust the batch color to that of the standard. Use the calibration of the Master Color Effect Chart and the variable scale of the Colorimeter-Chart plotting device to make this measurement. In the specific case of our example the following results are obtained:

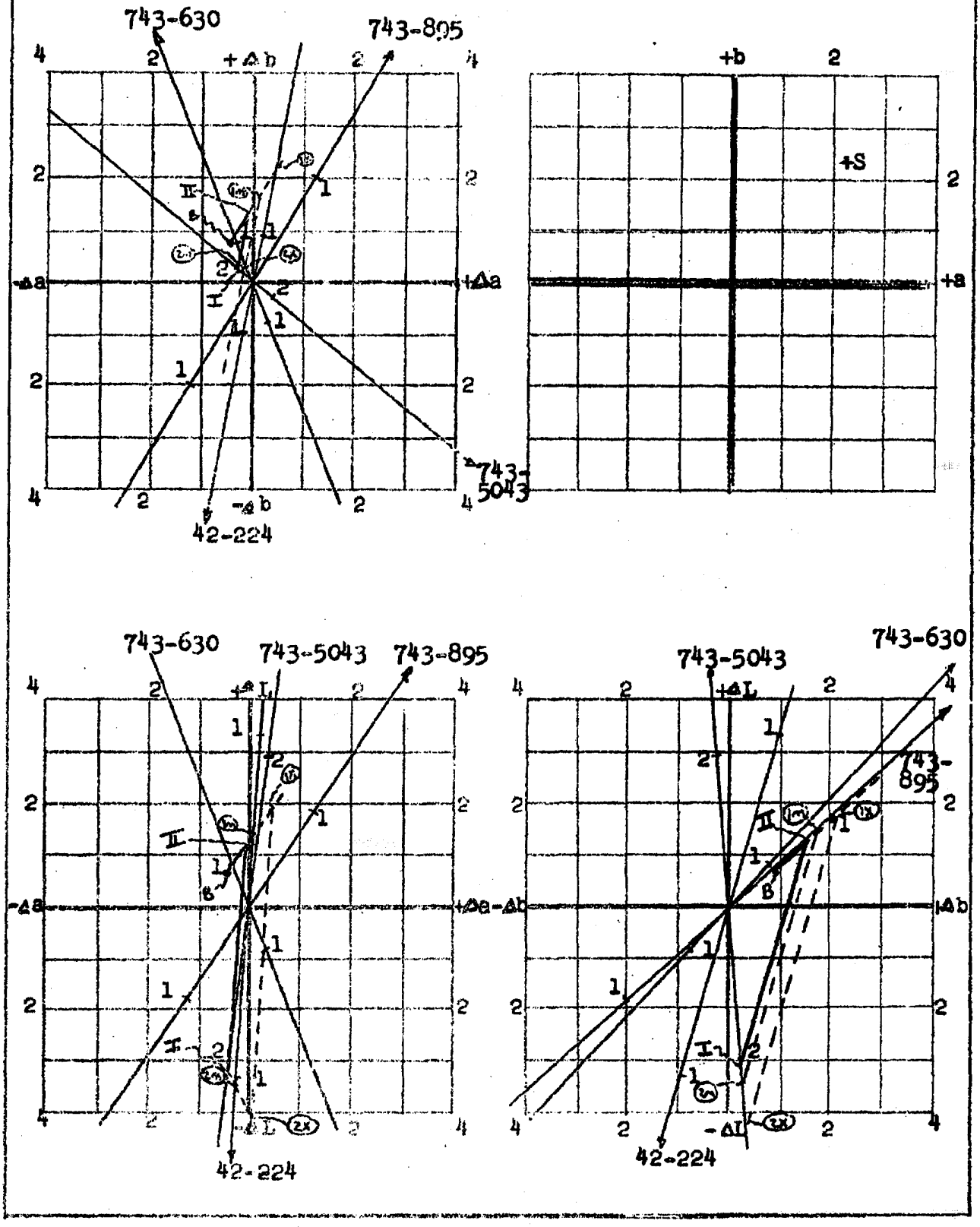
Colorant A (743-895) = 0.21 lbs./100 lbs. of batch
Colorant B (42-224) = 1.11 " / " " " "
Colorant C (743-5043) = 1.76 " / " " " "

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Figure XXIV

Colorimeter-Chart Color Adjustment System

- Example -



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The successful application of the Colorimeter-Chart Color Adjustment System is based upon several limitations. They are:

1) Use of strength standardized colorants. Changes in the strength of the colorants will result in changes in the calibration of the color effect charts.

2) The colorant blend must be essentially color stable when agitated in the wet. Each incremental color drift changes the ratio and quantity of colorants required for color adjustment.

3) The accuracy of the system is limited to the accuracy of the color measurement reproduction.

4) The system should not be indiscriminately applied to colors containing over 90-95% of type 2 colorants (note page I-20).

The colorimeter-Chart Color Adjustment System technique as described above may be applied to the shading of metallic colors with only slight modification. The technique of operation would be essentially the same for metallic as for non-metallic colors. The essential advantage of the technique is the simplicity and rapidity with which shading "hits" can be obtained and the inherent accuracy of the system which should reduce the number of shading "hits" and improve the turnover of production blending mixers.

This system has one disadvantage. It would require a separate "master color effect chart" for each color formulation to be brought under this mode of control. However, the data for these charts is very simply obtained and the charts are easily prepared.

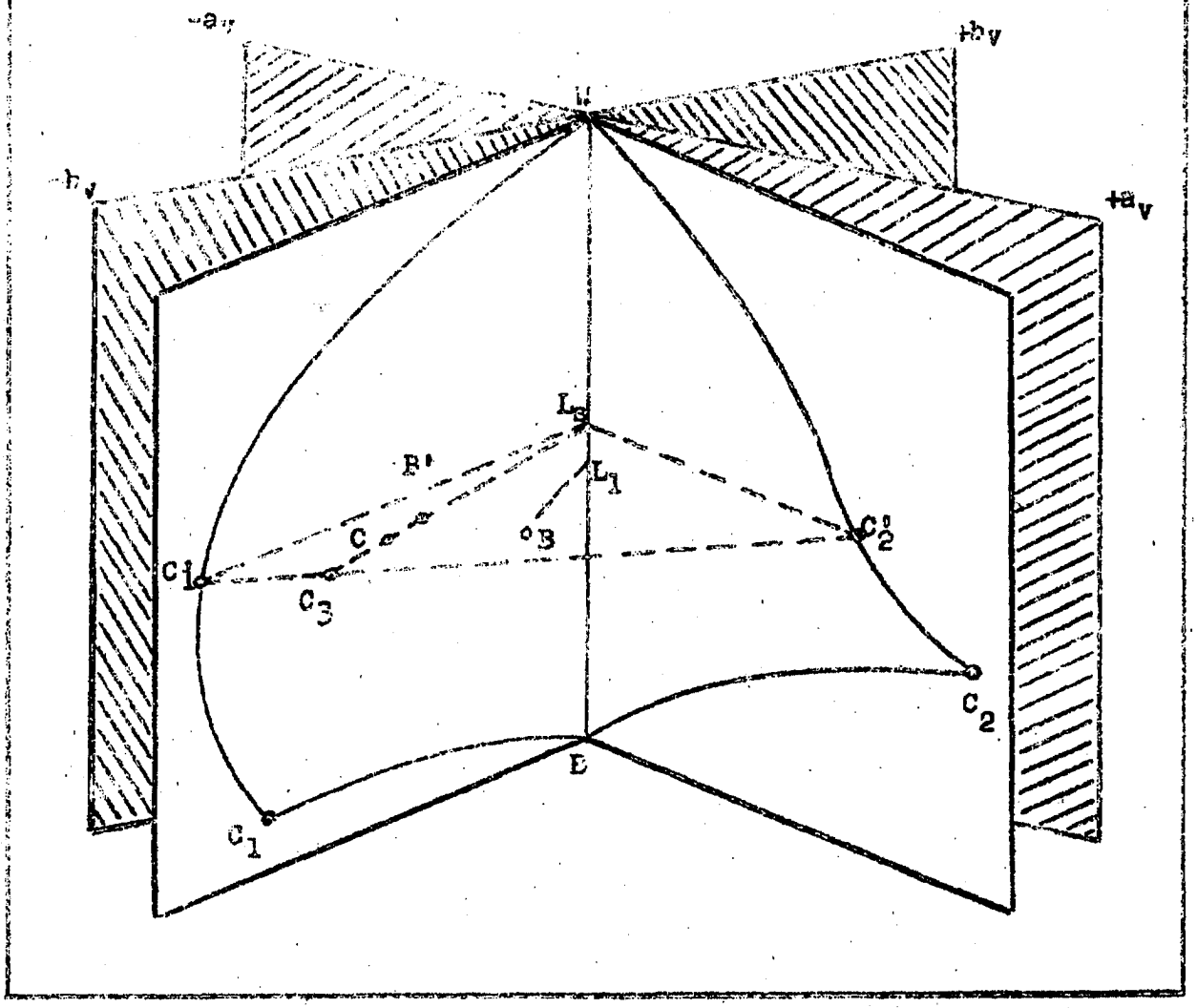
Mathematical Shading of Colors

The second improved method of shading production colors covers the mathematical calculation of the shading "hit" using the techniques of the Mathematical Color System. The basic techniques are similar to those of color formulation with only slight modification. Assume that color (C) has been matched by preformulation but for some reason the batch has a color (B) which differs from the standard (C) in (ΔL) (Δa_V) and (Δb_V). (Note the Vectoral Coordinate plot of this situation in Figure XX'.) One of the advantages of the Mathematical Color System is the fact that any combination of pigments can be treated as a single pigment having the vector color characteristics (A_L, A_a and A_b) which can be either readily determined or calculated from the known composition of (B). The ratio of batch (B) and colorant (C_1) necessary to match the hue of the standard can be readily determined by calculating the proportion of the (A_a) and (A_b) color characteristics of (B) and (C_1) necessary to match the hue (a_V/b_V) of the standard (C). Once this proportion has been determined a new set of (A_L), (A_a) and (A_b) color characteristics can be calculated for the (B,C_1) blend. From this point the matching of the standard (C) proceeds in the same manner as was previously discussed for the formulation of a color. The amount of the colorant blend (B C_1) which should be added to the starting white (W) to obtain the lightness (L) of the standard (C) is next calculated. The saturation (B') of the (B C_1) plus white (w) blend is obtained.

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Figure XXV

Mathematical Shading of Colors



Since, in the specific case of our example, the saturation (B') of the (W,B,C_1) combination is less than that of the standard, the overall formulation corresponding to (B') contains too much black in the form of neutral gray. The only way to remove the black from the formulation is to add sufficient of the white (W), Colorant (C_1) and Colorant (C_2) to reduce the black to the desired level and therefore increase the saturation from (B') to that of the standard (C).

This is achieved by formulating mathematically the white (W)/Colorant (C_1)/Colorant (C_2) composition corresponding to the maximum saturation (C_3) obtainable at the lightness (L_s) and hue of the standard (C). The standard (C) is then matched by combining the formulations corresponding to (B') and (C_3) in the proper proportion to provide the desired saturation. The direct effect of this calculation is to move the batch color from (B) to (C) directly.

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The shading of metallic colors follows the same general procedure with adequate compensation to allow the matching of the "two-tone" characteristics of the standard as well as its lightness, hue and saturation.

Other Applications of the Mathematical Color System

The use of the Mathematical Color System is not limited to the preformulation and shading of colors. Color is not only the end product of our manufacturing process, but also may be a valuable tool, serving to define and control many of the variables which ultimately affect the efficiency of the production of colored finishes. As an example, consider the problems associated with the use of a specific pigment. These problems include the evaluation of a pigment either as a new pigment or an alternate source of supply for an existing pigment, the dispersion of the pigment, and the standardization of the pigment dispersion. The application of the fundamental principles of color to each of these problems results in a more thorough understanding of the problem and the creation of methods designed to resolve the problem. For reasons of clarity, we will examine these problems in reverse order.

Standardization of Pigment Dispersions

The color of pigment dispersions, because of the inherent variation in the pigment, vehicles and the dispersion process, varies widely from batch to batch. This variation includes not only the lightness, hue and saturation of the pigmented base, but also its "tinting strength" which is a measure of the amount of the pigment dispersion which must be added to white to produce a tint of fixed lightness. In terms of the Mathematical Color System, the Tinting Strength is a measure of the length of the lightness color characteristic (A_L) defined on page (I-17). Evaluation of the lot to lot color variability of color pigment dispersions indicated that the Tinting Strength was responsible for 80-90% of the inherent lot to lot variability of pigment dispersions.

A technique was developed in the early 1950's at the Toledo Plant which allowed the adjustment and control of this Tinting Strength variation. Briefly summarized, this technique involves the use of non-pigmented vehicle or solvent to adjust the level of dispersed pigment in the pigmented base to the point where a fixed blend of this adjusted pigmented base with white or black would always have the same lightness. The successful development of this concept was a big step forward in that the color variability inherent in these pigmented bases was cut by 80-90%. The technological improvement of this system was immediately exploited in the "Duco"* and "Dulux"* Refinish Mixing Machine Systems which utilized a fixed formulation for matching colors in the field and have shown increasing commercial success with each passing year. The system has also offered considerable aid to visual shading in commercial production, in that the shader is working with essentially reproducible colorants.

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Technological progress in this direction ceased with the development of the original techniques of Tinting Strength Standardization. The intervening period has seen the development of improved tests and mechanical manipulations within the original scope of the Tinting Strength Standardization concept.

This state of technological "suspended animation" resulted from the time interval inherent between the inception of a basic idea and its full scale commercialization on a production scale. While the production organization was equipped to handle the production of relatively small volumes of the Tinting Strength Standardized Refinish Mixing Machine colorants at two or three locations, it was not equipped nor trained to apply the concept of Tinting Strength Standardization across the board. The intervening period has been primarily concerned with the installation of suitable equipment, the training of personnel and the development of suitable techniques to handle the Tinting Strength standardization of difficult lines such as 34 line bases. Many other lines remain to be standardized before this program can be considered complete.

Late in 1958, the Ajax Finishes Plant of Du Pont of Canada, Ltd., found that a substantial increase in their 15 Line Refinish Mixing Machine business would result if closer color reproduction of the fixed formulations could be achieved. This led Ajax into a "crash program" designed to reduce their lot to lot color variation in 15 line to 0.5 NBS units vs. the 1.5 to 2.5 NBS range of U. S. manufactured 15 line colorants.

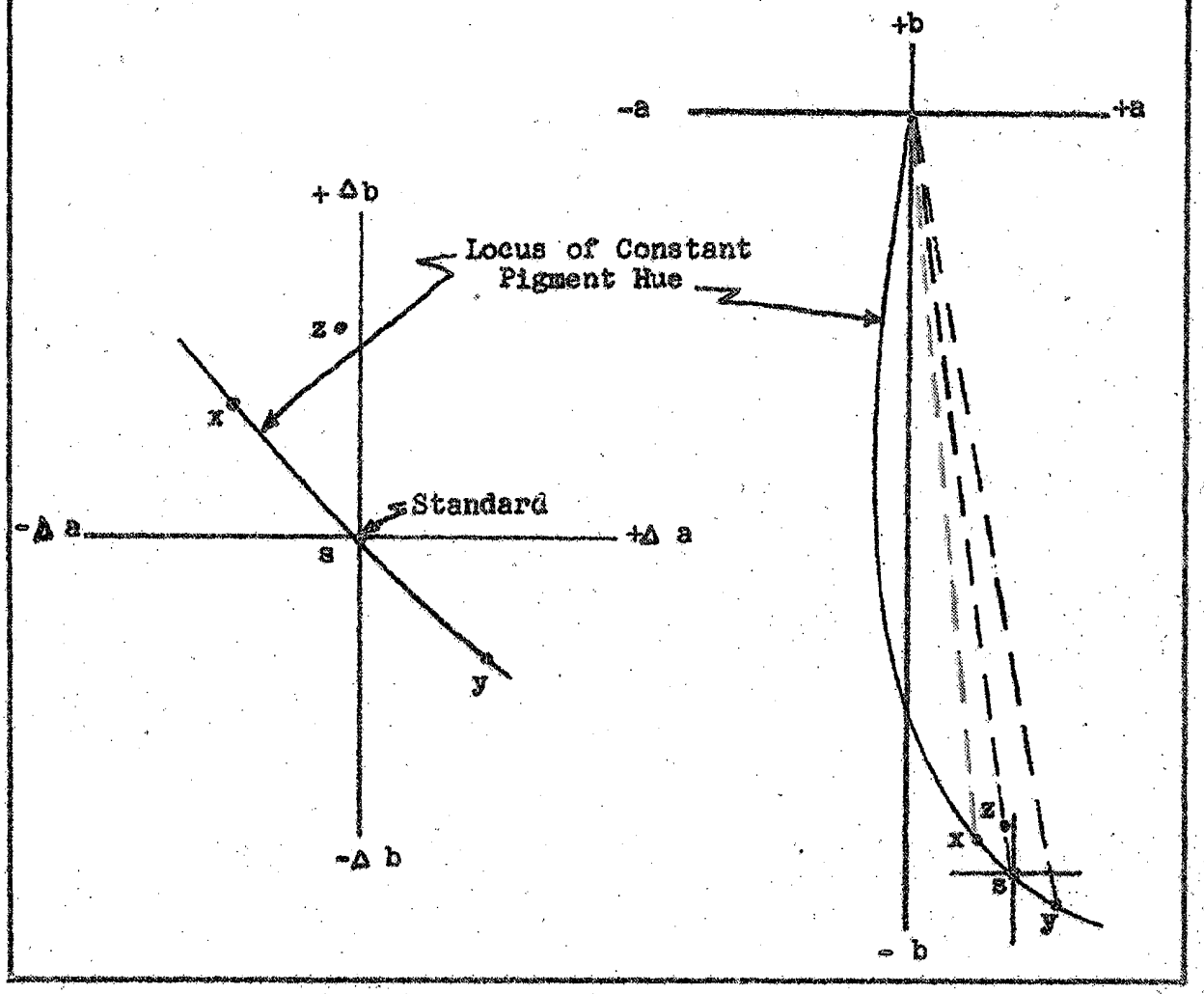
The above situation emphasizes an existing color control problem which has been largely overlooked in the manufacture of Tinting Strength standardized bases. The bulk of the lot to lot variation encountered in the production of pigmented bases is in the tinting strength of these bases. The use of the current strength standardization procedures will result in the elimination of 80-90% of this lot to lot deviation providing the masstone lightness of the pigmented base does not vary too widely from lot to lot. However, we do not exercise any direct control over lot to lot variations in hue, saturation or masstone lightness of the pigmented bases, even of the tinting strength standardized bases. Thus, there is an inherent color variation in blends of 15 line or 269 line color bases which is uncontrollable by present techniques. To control and reduce the magnitude of this inherent color variation, it will be necessary to develop techniques which will control the three variables listed above. In order to understand the necessity for controlling these variables and the techniques involved, it is necessary to segregate the effects of each of these variables on the finished product colors.

Hue - Probably the most universally recognized color variable inherent in the tinting strength standardized color bases is hue. Some degree of color control is obtained in 15 line through the selection of specific lots of 42 line color base which will produce 15 line color bases of acceptable lot to lot variation. However, since this selection is made in the curvilinear Modified Adams Coordinate System, there is considerable confusion existing with respect to hue and saturation variation because pigment hues are not represented in this coordinate system. Consider Figure XXVI which represents the locus of lot to lot variation of a typical blue pigment.

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Figure XXVI

Visual Interpretation of Lot to Lot Pigment Color Variation
Modified Adams' Coordinate System



Points "X", "Y", and "Z" in Figure XXVI represent three different batches of our blue pigmented base let-down to constant lightness (i.e., "equivalent" tinting strength) with the standard white. Under the Modified Adams Coordinate System of color evaluation, batch "Y" would be evaluated as "red-purple" with respect to standard and batch "X" as "green-yellow" with respect to standard, a judgment with which visual interpretation would agree. Batch "Z" would appear visually to be of the same hue as the standard but less saturated. Actually, when the curvilinear locus of the blue pigment hue is considered, it becomes apparent that batches "X" and "Y" are of the same hue as the standard but differ in saturation, "Y" being more saturated and "X" less saturated than standard. Conversely, batch "Z" differs both in hue and saturation from the standard. Current selection techniques are therefore completely erroneous in this case.

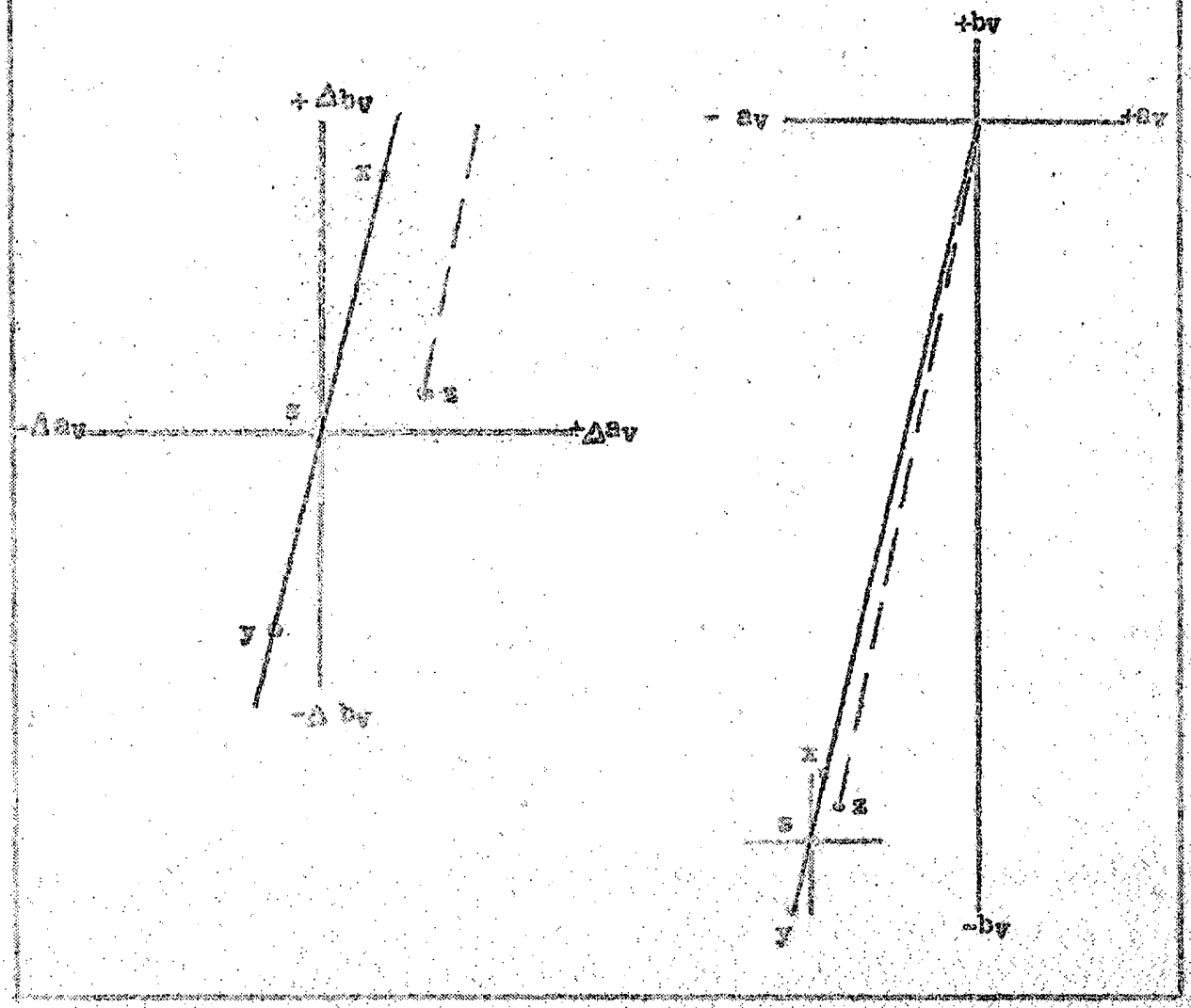
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Under the proposed Vectoral Coordinate System (VCS), these differences in interpretation will disappear. (Note Figure XXVII) Batches "X" and "Y" will be on the same hue line as the standard, "X" will be closer to the neutral axis than the standard and therefore be of lower saturation, and "Y" will be further from the neutral axis than the standard and will be rated as "more saturated". Point "Z" will indicate a batch which is both redder in hue and less saturated than standard.

Unfortunately the determination of the VCS is not sufficiently advanced to allow routine use for this purpose. However, the locus of the color pigment hue can be approximated by selecting the most saturated tinting strength blend and adding small quantities of neutral gray to reduce the saturation along the approximate locus of the pigment hue.

Figure XXVII

Interpretation of Lot to Lot Pigment Color Variation
Vectoral Coordinate System

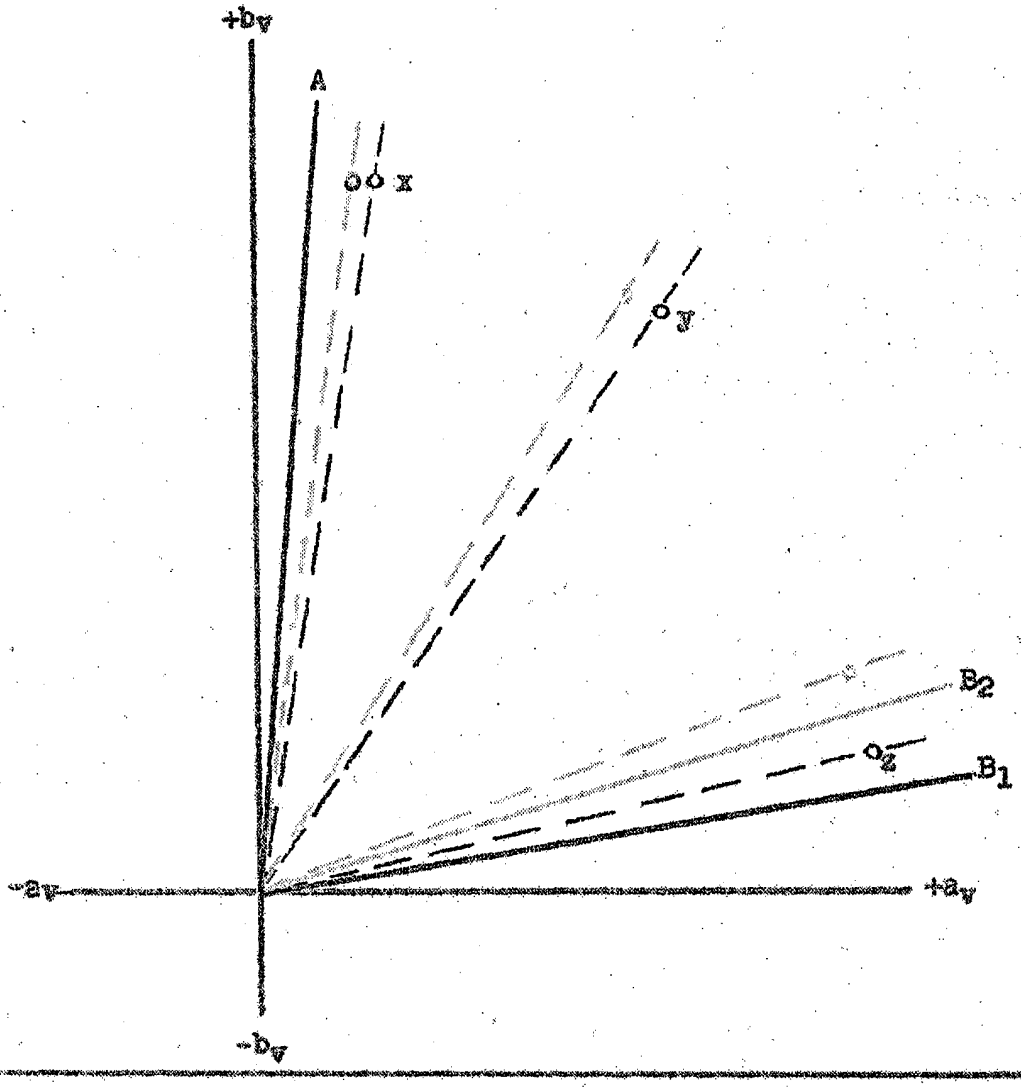


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The primary effect of lot to lot hue variations is to change the proportions of the color pigment bases required to obtain a specific hue. The effect of this lot to lot variation on the proportions of colorants "A" and "B" required to make colors "X", "Y" and "Z"

Figure XXVIII

Effect of Changes in Pigment Dispersion Hue on the Color of a Fixed Formulation Vectoral Coordinate System



will vary widely depending on the hue of the color to be matched. The hue of color "X", (Note Figure XXVIII) for example, will not be greatly affected by a change in the hue of the pigmented base from the original B_1, with which it was originally formulated to "B_2". This is primarily because the ratio of "A" to "B" colorant is so large that a hue change in colorant "B" will have virtually no effect on the blend of the two colorants.

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Color "Y" will reflect more strongly the result of a hue change in colorant "B" because the ratio of colorant "A" to colorant "B" in matching color "Y" is much smaller than in the case of color "X" and the higher proportion of colorant "B" in color "Y" would reflect more of the hue change in "B".

Color "Z" represents the condition of a color which can be made with colorants "A" and "B_1", but cannot be made at all with colorants "A" and "B_2". This specific color illustrates the principle that the closer the color is to the hue of one of the colorants which varies in hue, the more drastic must be the formula revision to compensate for the change in hue.

Saturation - As can be seen from the previous discussion of current hue measurement and control techniques, there is a considerable misinterpretation of Modified Adams Coordinate data which results in the current technique of hue control being applied to saturation as well. However, there is no direct control, other than batch selection, applied to saturation differences of the pigment bases. The effects of batch to batch saturation differences in the finished 15 line color formulas is primarily reflected in changes in the saturation of the color made from the colorant. This saturation effect will increase in formulations requiring a high proportion of the affected colorant in the color blend to match the hue, and decrease where only a small proportion of the colorant mixture is composed of the affected pigment base. The general comments made on hue above are also applicable to saturation.

Masstone Lightness - The effects of changes in the masstone lightness of the pigmented base are perhaps the least understood of the three variables. Since the color effect in a lightness direction is a function of the masstone lightness, it is apparent that two lots of the same pigmented base, which differ in masstone lightness and have been strength standardized to the same level, will be of equal strength at the lightness at which they are standardized. Consider the case of two lots of pigmented base "A" and "B" which have been strength standardized at lightness "L" but differ in masstone lightness (Note Figure XXIX).

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Figure XXIX

Effect of Change in Masstone Lightness on
Lightness of Fixed Color Blend with White

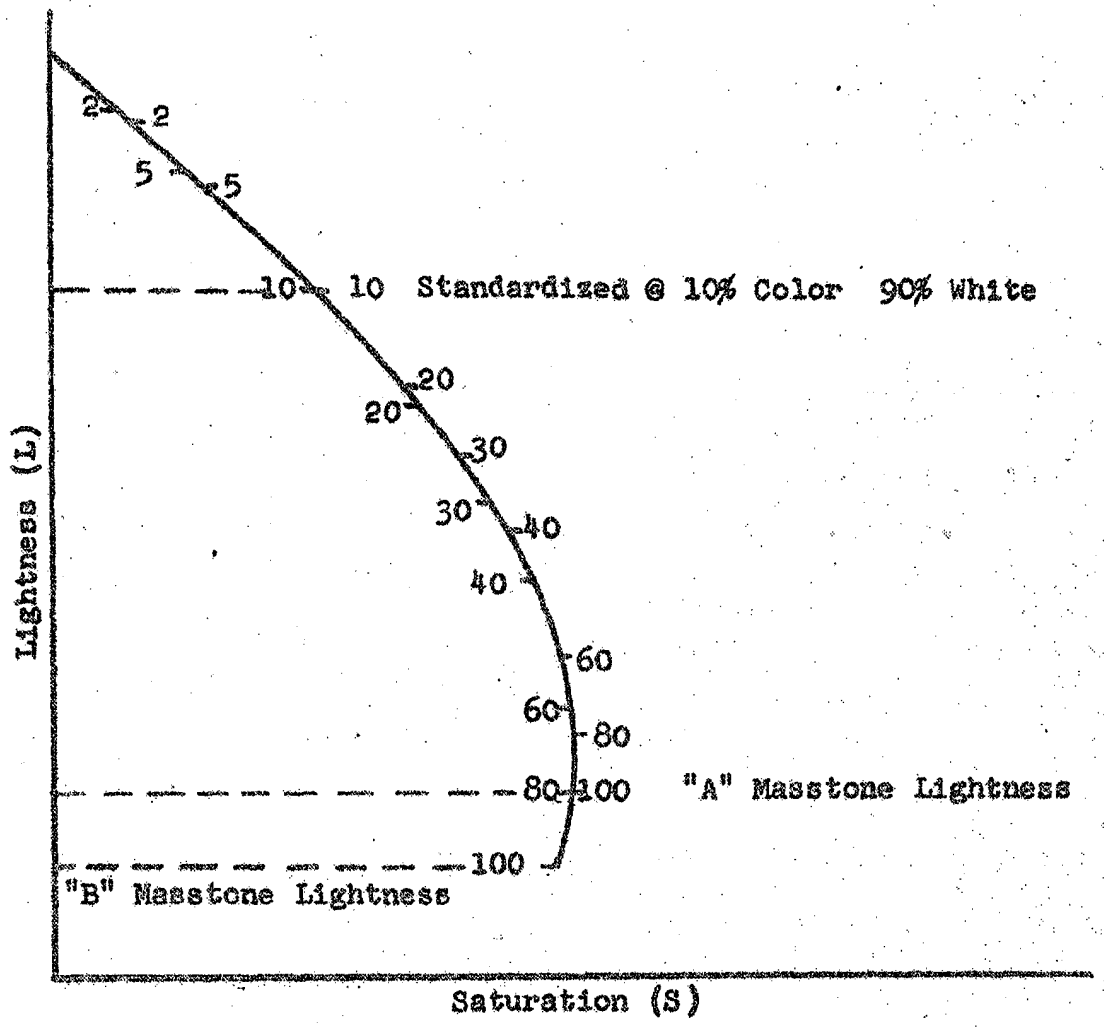


Figure XXIX illustrates the effect of a difference in masstone lightness between two batches of pigment base "A" and "B" when let down in the same proportion into the same white and standardized at the 10% color, 90% white level. It is interesting to note that the difference in masstone lightness can contribute to color differences in a fixed formulation in both the lightness and saturation directions. The differences in saturation are usually the greatest in the light pastel region where the shape of the Lightness vs. Saturation curve indicates that a small change in lightness will result in a big change in saturation. As the basic masstone lightness is approached, the difference in the blended color lightness will increase for a given formulation.

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Control of Mixing Machine Colorants - The previously discussed color results are based on hypothetical pigmented bases which varied in only one of the color variables; masstone lightness, hue and saturation. In actual practice, these color bases rarely vary just in masstone lightness, hue or saturation. A great percentage of the batches vary in all three color components, which vastly complicates the assessment of these variables on the color of a finished product made to a fixed formulation. The situation is further compounded by the use of tinting strength standards formulated for weighing rather than color accuracy. This is particularly true in the case of certain yellows and oranges which were strength standardized in blue formulations. These formulations were basically in error for color control purposes for two reasons:

1) They contain such a high percentage of blue from a strength basis that color changes in the hue and saturation direction in the yellow or orange bases are minimized, resulting in little direct color control over pigmented bases which are used mainly in masstone quantities.

2) It is basically inconsistent to attempt to control the hue of yellow and orange pigment through mixture with blue since there is a drastic hue shift with small differences in lightness.

This situation could be considerably improved through the substitution of yellow-black or orange-black blends at a much higher lightness for the current tinting strength formulations. The use of a lighter blend would reflect the variations in the hue and saturation of the yellow and orange bases much more accurately and the elimination of the blue-yellow and blue-orange blends would eliminate the drastic change of hue with lightness. Improvement in the reproducibility of 15 line and 42 line sprayouts, particularly in masstone sprayouts, would assist in tightening specifications.

These suggestions amount to mechanical manipulations designed to achieve greater accuracy in color standardization. These modifications do not basically attack the problem of tightening the lot to lot variability of 15 line Mixing Machine bases to conform to the 0.5 NBS unit tolerances desired at Ajax. The solution of this problem is feasible through more careful selection of 42 line bases of sufficiently small variation in hue, saturation in masstone lightness. However, as the tolerances of the 15 line Mixing Machine bases are tightened, a higher and higher proportion of the current 42 line bases will become unsuitable for conversion to 15 line.

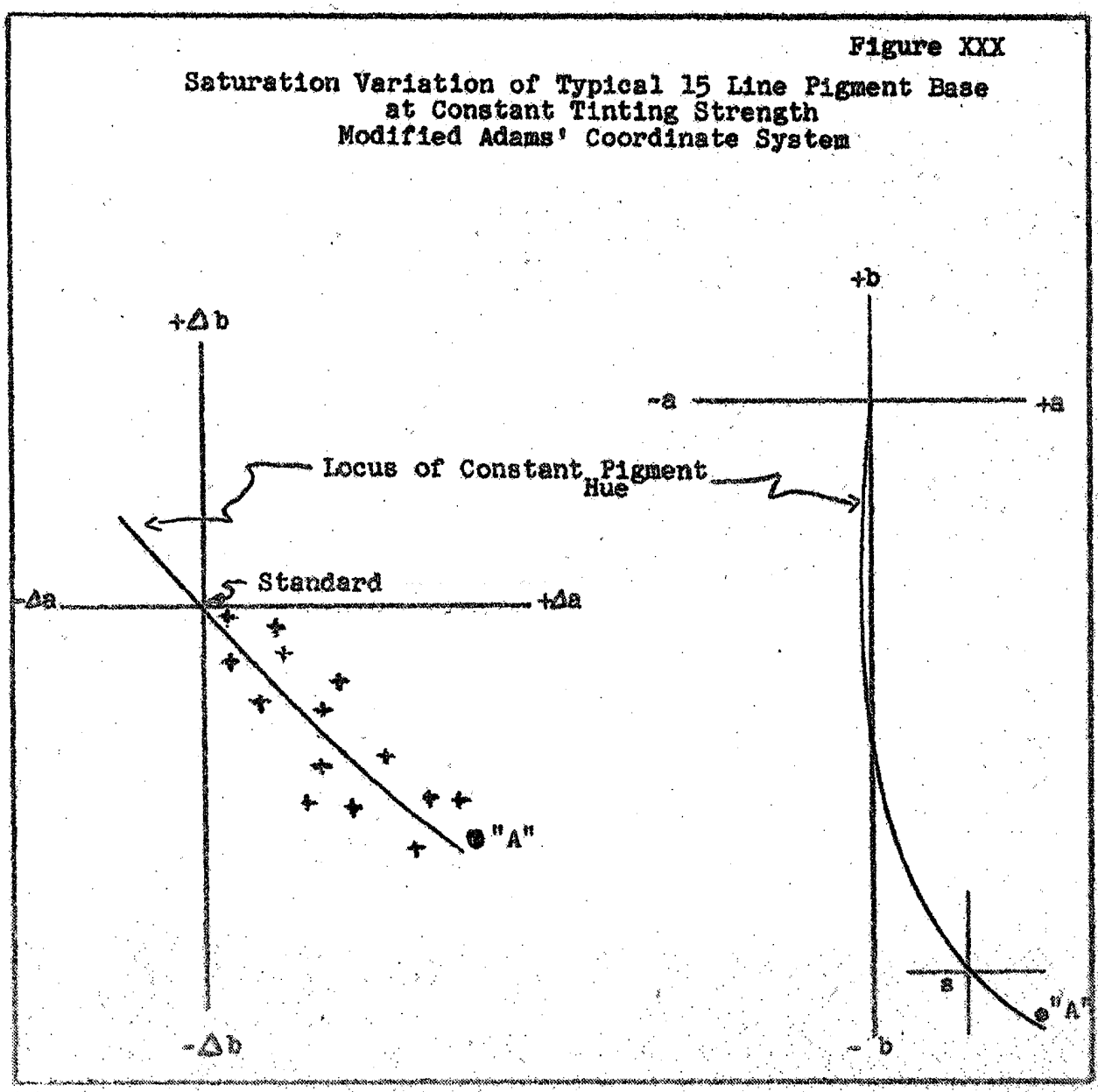
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The selection of active remedial procedures is dependent upon the type of color variation encountered in the batch to batch production of the specific pigment base under investigation. The relationship of this variation to the color standard for the particular pigment base is also of importance in developing a technique for controlling these variations in hue, saturation and masstone lightness.

With this background in mind, it was possible to analyze the data accumulated by R. H. Vining on 15 line production at the Ajax Plant of Du Pont of Canada. The majority of the 15 line color pigment bases made at Ajax appear to vary from standard mainly in the saturation direction when examined at constant tinting strength. (Note Figure XXX.) The bulk of these batches was more saturated than the standard. Under these specific conditions, the following corrective measures were proposed.

Figure XXX

Saturation Variation of Typical 15 Line Pigment Base
at Constant Tinting Strength
Modified Adams' Coordinate System



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1) Select the most saturated batch "A" as revealed by the constant tinting strength plots of Δa and Δb.

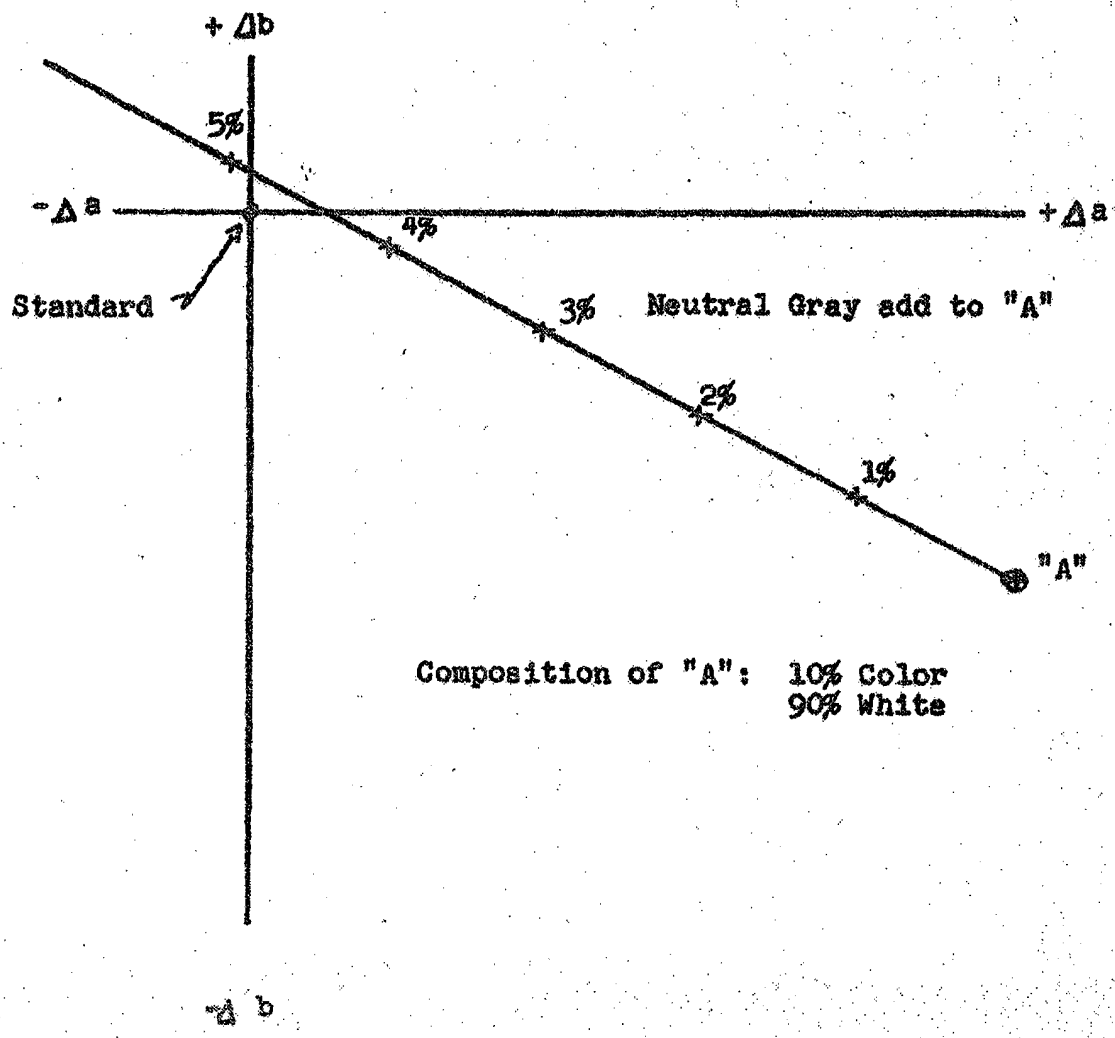
2) Add incremental quantities of neutral gray of the same lightness as the Tinting Strength Standard to the saturated batch "A". This will provide a scale of neutral gray correction for these batches to adjust the saturation of the individual batches to that of the standard. (Note Figure XXXI.)

Figure XXXI

Adjustment of Color Pigment Base Saturation

Step 1: Determination of Neutral Gray Adjustment Scale

Modified Adams' Coordinate System



Composition of "A": 10% Color
90% White

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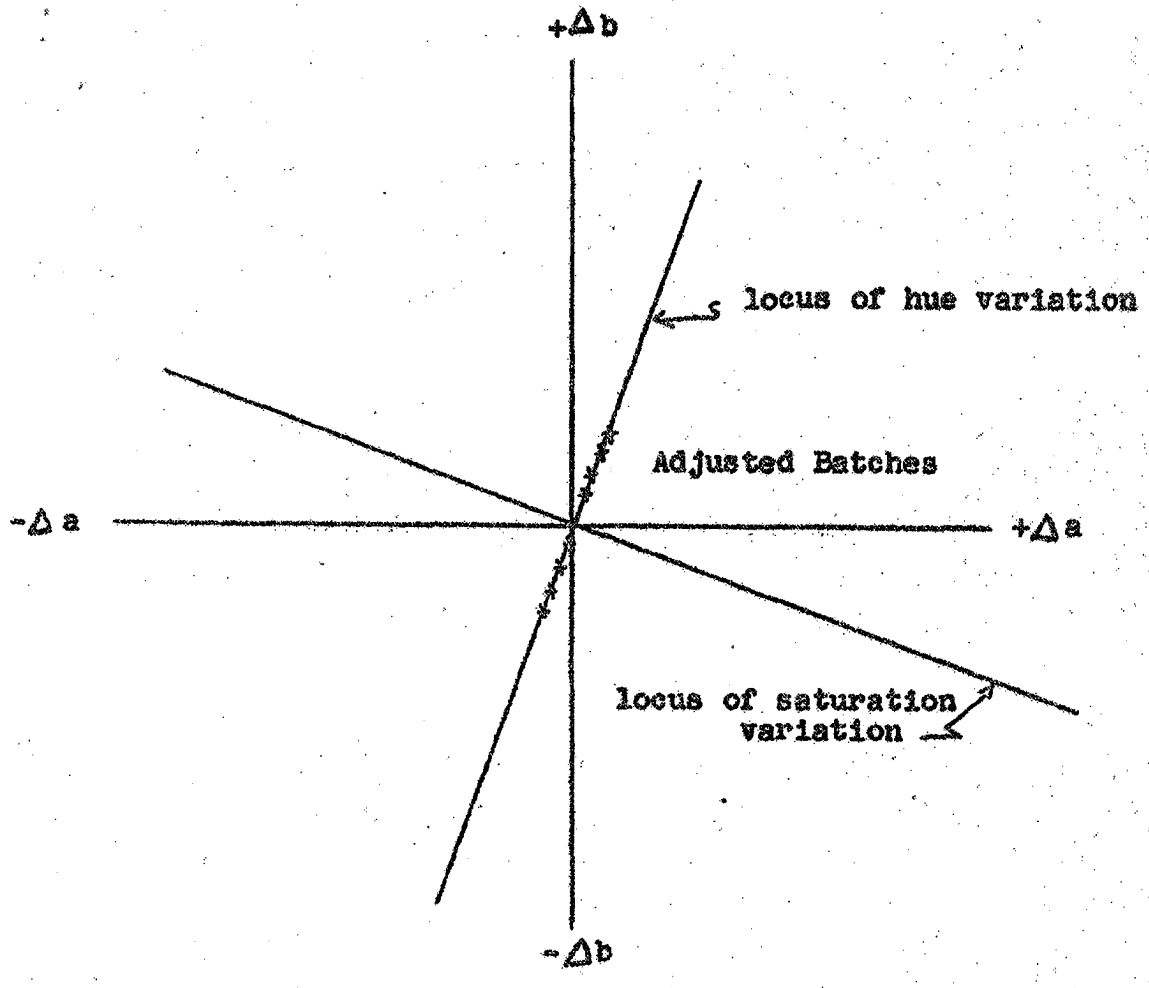
3) Once this scale is established, it can be used in determining the amount of neutral gray necessary to correct the saturation of the remaining batches to that of the standard. The corrected batches will then have essentially constant saturation but will vary from the standard in hue as shown by comparing FigureXXXI with Figure XXXII.

Figure XXXII

Adjustment of Color Pigment Base Saturation

Step 2: Results of Saturation Adjustment with Neutral Gray

Modified Adams' Coordinate System



The locus of saturation deviation illustrated in Figure XXXII is a line parallel to the neutral gray correction curve of Figure XXXI. The locus of the hue deviation of the corrected batches will be perpendicular to the locus of saturation correction.

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4) Knowing the amount of neutral gray of the lightness of the Tinting Strength Standard necessary to correct the specific batch to that of the standard and the composition of both the neutral gray and the Tinting Strength let-down, it is then possible to calculate the amount of black pigment dispersion necessary to adjust the saturation of a given weight of the color pigment dispersion to equal that of the standard.

It should be pointed out at this point that the neutral gray is added so that the lightness of the Tinting Strength let-down is relatively unaffected. Actually, the white contributes nothing to the saturation reduction. The amount of the saturation reduction is determined by the amount of the black pigment dispersion used. The above procedure will determine the amount of black pigment dispersion which must be added to the color pigment dispersion to adjust the saturation vs. lightness curve to that of the standard. (Note Figure XXXIII.) This black is applied in the form of a second neutral gray of known composition, the amount of black controlling the amount of neutral gray added. With suitable calibration, the Masstone Lightness of the specific batch can be adjusted either upwards or downwards to a limited degree, to more closely agree with that of the standard. This adjustment can be made by varying the lightness of the added neutral gray for the specific condition of Masstone Lightness of the batch.

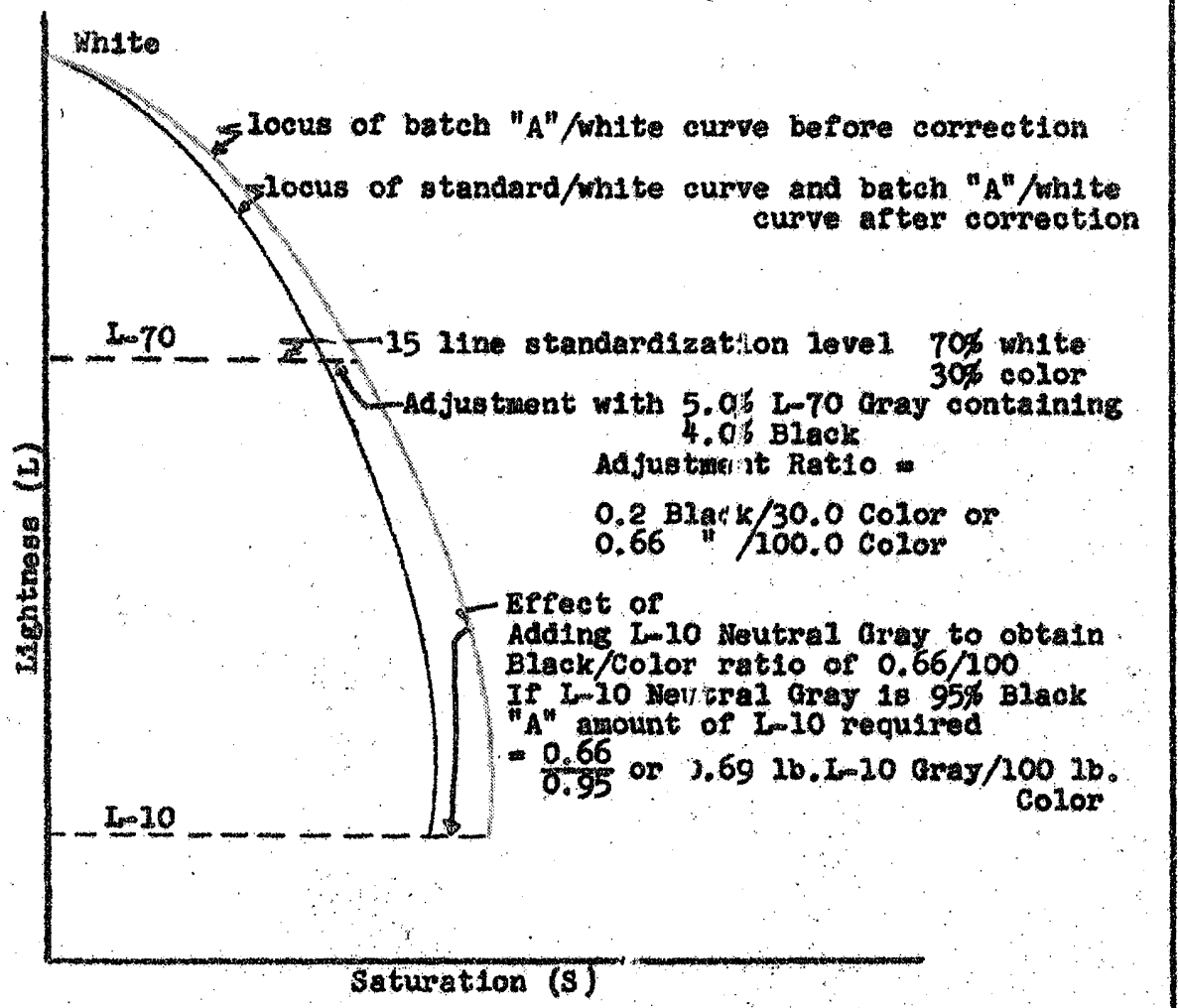
The basic purpose of adding black, in the form of a neutral gray, to a colored pigment dispersion, is to adjust its saturation characteristics to correspond to those of the standard. In this manner, assuming that no hue or masstone lightness differences exist between the color standard and the specific batch, the saturation vs. lightness curves of the two pigment dispersions will coincide (note Figure XXXIII) and their usage under conditions of the same strength, will result in color matches within a reduced tolerance.

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Figure XXXIII

Adjustment of Color Pigment Base Saturation

Step 3: The Mechanics of Neutral Gray Addition



Single color pigment bases vary not only in saturation but also in hue and masstone lightness. The effects of these variations have been previously discussed. To obtain satisfactory blended color reproducibility, it is necessary to be able to control saturation, hue and masstone lightness. If after the above saturation controlling procedures are applied, the lot to lot variation of the hue and masstone lightness is still sufficient to give blended color reproducibility in excess of the desired tolerance, further remedial procedures must be adopted. Experience gained to date indicates that the number of pigments where lot to lot hue or masstone lightness differences are sufficient to cause difficulty are relatively limited. Difficulties of this type apparently are inter-related in that the pigments which have an unacceptable hue variation also have an unacceptable variation in masstone lightness. The situation is apparently caused by either the pigment itself or poor reproducibility of the dispersion operation. Preliminary evidence indicates that some of our dispersion formulations may be unduly sensitive to the variations inherent in the lot to lot manufacture of pigment dispersions.

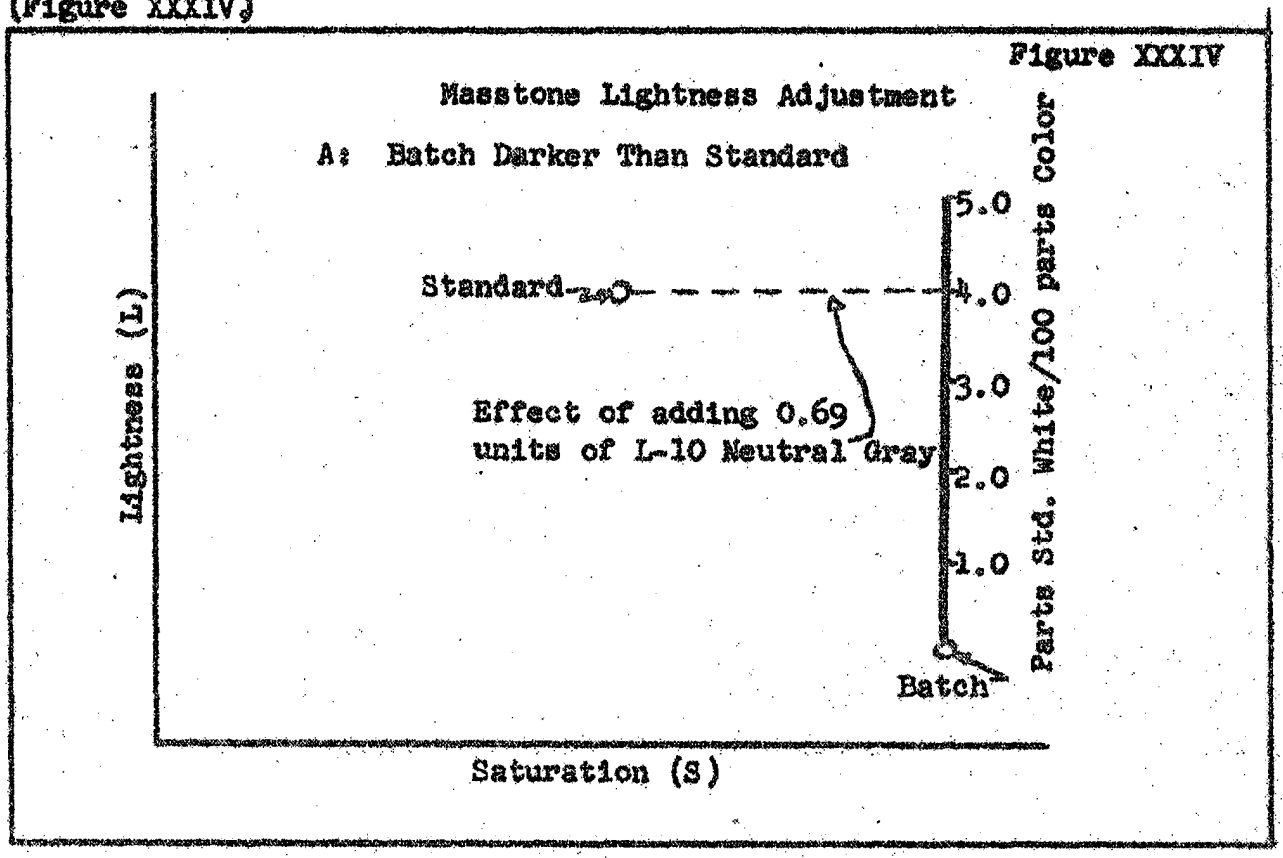
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The use of the "neutral gray standardization" technique is not limited to the adjustment of saturation differences between a batch and a standard. Moderate differences in the masstone lightness of the batch can also be compensated for at the time of saturation adjustment. The specific technique used depends upon the relative masstone lightness of the batch and the standard.

A: Batch Darker Than Standard

A simple nomograph can be set up for this condition showing the effect of incremental white adds to a strength standardized batch. (Figure XXXIV)

Figure XXXIV



If the batch is darker than standard, the difference in the masstone lightness determines the amount of white necessary to adjust the masstone lightness of the batch to standard. With solid color pigment dispersions (i.e., essentially non-transparent) there is apparently no limit to the amount of white which can be used for masstone lightness adjustment. In the case of the transparent pigment dispersions used for metallic colors, the use of white is obviously limited by the effect of the white on the "two-tone" of the pigment dispersion. Over a normal masstone lightness variation there will be no appreciable effect on the "two-tone" characteristics of the adjusted transparent pigment. This is because a darker transparent pigment dispersion has an inherently greater "two-tone" than the standard pigment dispersion. Therefore, the addition of the white dispersion required to adjust the masstone lightness also serves to reduce the "two-tone" toward that of the standard.

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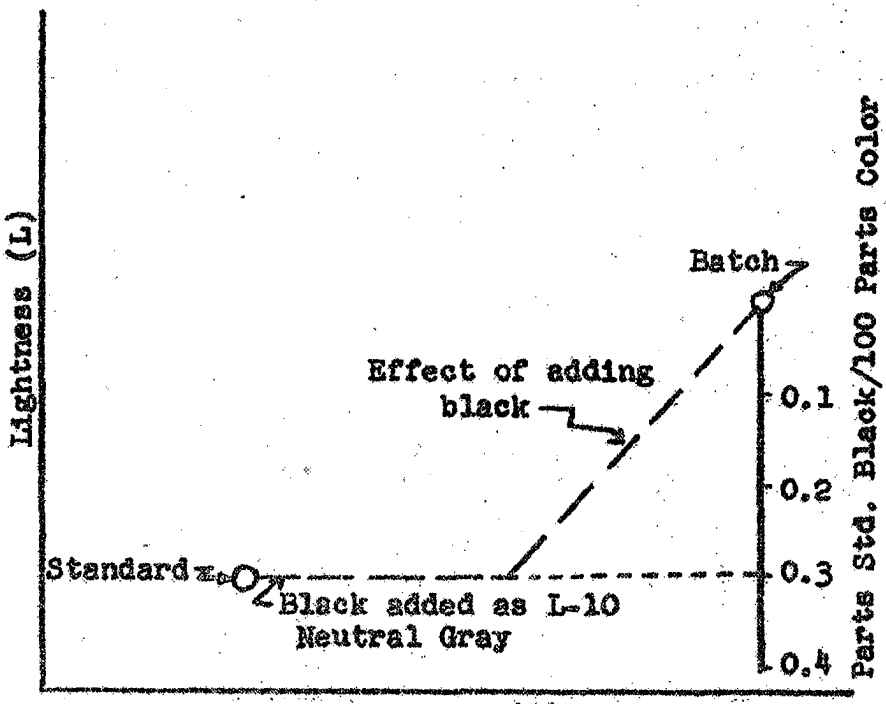
After sufficient white has been added to adjust the masstone lightness of the batch to standard, the conventional neutral gray addition is made. The neutral gray used will be of the same lightness as the standard dispersion masstone lightness. The amount of neutral Gray used will be limited by the previously determined amount of black necessary to adjust the saturation of the batch to that of the standard.

B: Batch Lighter Than Standard

A similar nomograph can be developed for this condition showing the effect of adding incremental amounts of black to a strength standardized batch upon the masstone lightness (Figure XXXV). There is a basic difference inherent in the addition of black. In addition to its effect on the masstone lightness, black also has a saturation reducing effect. Therefore, the amount of black which is added is limited by the black to color base ratio determined at the standardization ratio.

Figure XXXV

Masstone Lightness Adjustment
B: Batch Lighter Than Standard



If sufficient black can be added to adjust the masstone lightness of the batch to that of the standard, the remaining black can be added as a neutral gray of the same lightness as the masstone lightness of the standard. The overall amount of black used in the lightness adjustment and the neutral gray add is limited by the previously determined amount of black necessary to adjust the saturation of the batch to that of the standard.

Some of the pigment dispersions vary sufficiently in hue and/or masstone lightness to preclude the use of the neutral gray standardization technique.

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There are two methods available for correction of these hue and masstone lightness differences.

1) Shading with chemically similar pigments. This method is the one most often proposed as a solution to the problem of obtaining batch to batch uniformity of pigmented bases. The basic problem inherent in such an approach is the multitude of corrections which must be made simultaneously to the pigmented base. Any shading correction must adjust the saturation, hue and masstone lightness as well as the tinting strength. This type of approach does not appear to be commercially feasible for routine factory production at this time.

2) Adjustment of formulation and/or grinding rate to provide conditions under which the effect of the lot to lot variations inherent in the dispersion operation are minimized. This approach has led to the development of the concept and techniques of "dispersion equilibrium" detailed on pages III-38 to III-71 of the "Color Handbook". Prelmminary information on application of "dispersion equilibrium" techniques has established the suitability of the concept to the prediction of specific grind rates to obtain dispersion equilibrium. In some cases, the use of these techniques indicates that the lot to lot variation inherent in the dispersion operation is not too significant. In other cases, the effect of these variations has been to produce significant color changes, particularly in the hue and masstone lightness of the pigment dispersion.

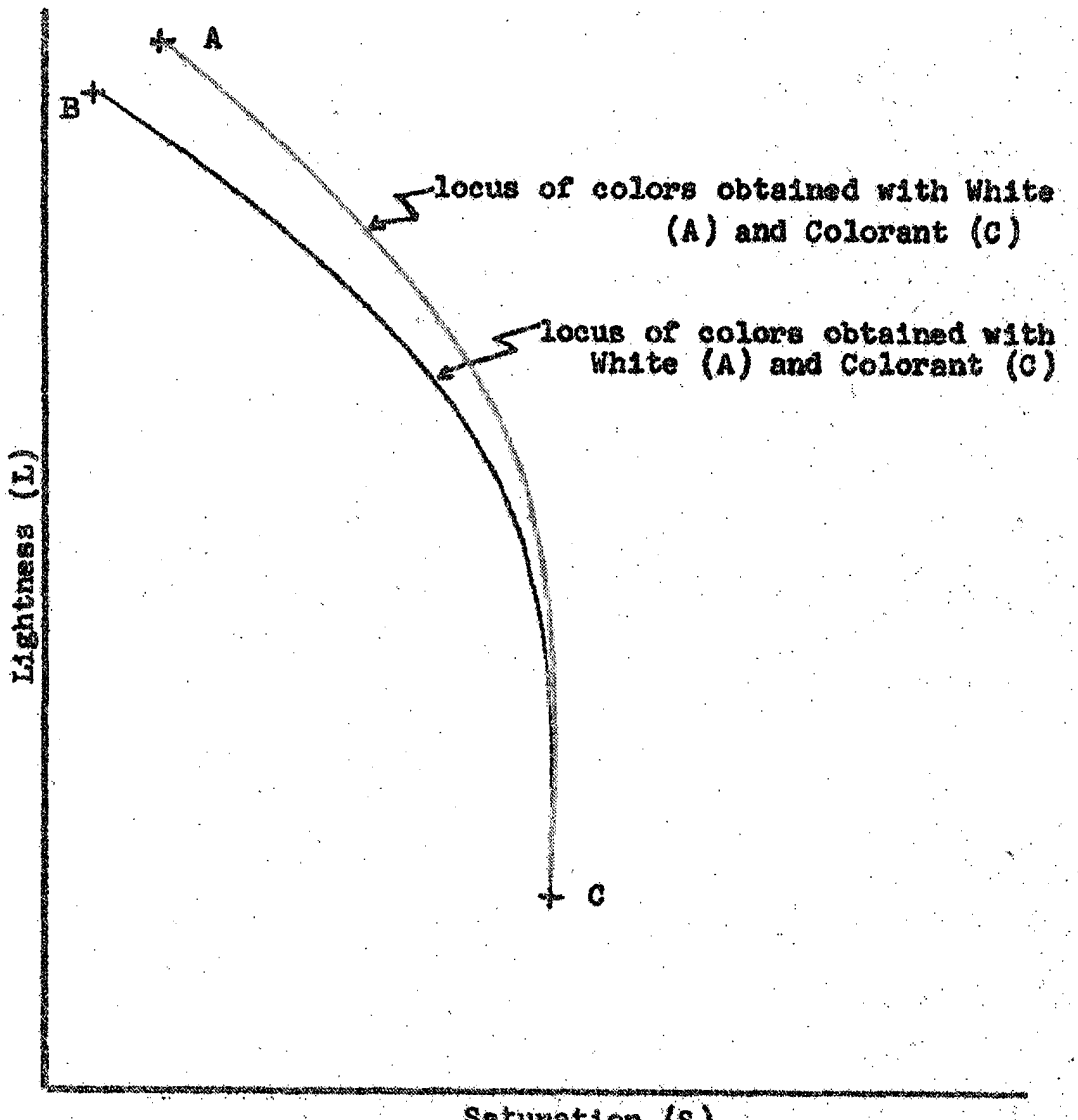
The important result obtained from the preliminary application of "dispersion equilibrium" techniques has been the reduction in hue and masstone lightness differences inherent in the dispersion process. There is substantial evidence that the same lot of pigment dispersed under conditions of "dispersion equilibrium" will show little variation in hue, saturation and masstone lightness from batch to batch. If a significant lot to lot color variation exists in various lots of pigment dispersed under these conditions, it is then possible to assign this variation directly to the pigment itself and the pigment supplier should be contacted with respect to improving his manufacturing operation.

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While the bulk of the foregoing discussion has been directed toward the adjustment of hue, saturation and masstone lightness difference in color pigment dispersions, the significance of these differences in neutral pigment dispersions should not be overlooked. Ajax has found significant differences in masstone lightness and saturation, which, in the case of the white pigment dispersion, have a considerable influence on the color reproducibility, particularly in the region of light pastel colors. (Note Figure XXXVI.)

Figure XXXVI

Influence of Saturation and Masstone Lightness of White Pigment Dispersions on Blended Colors



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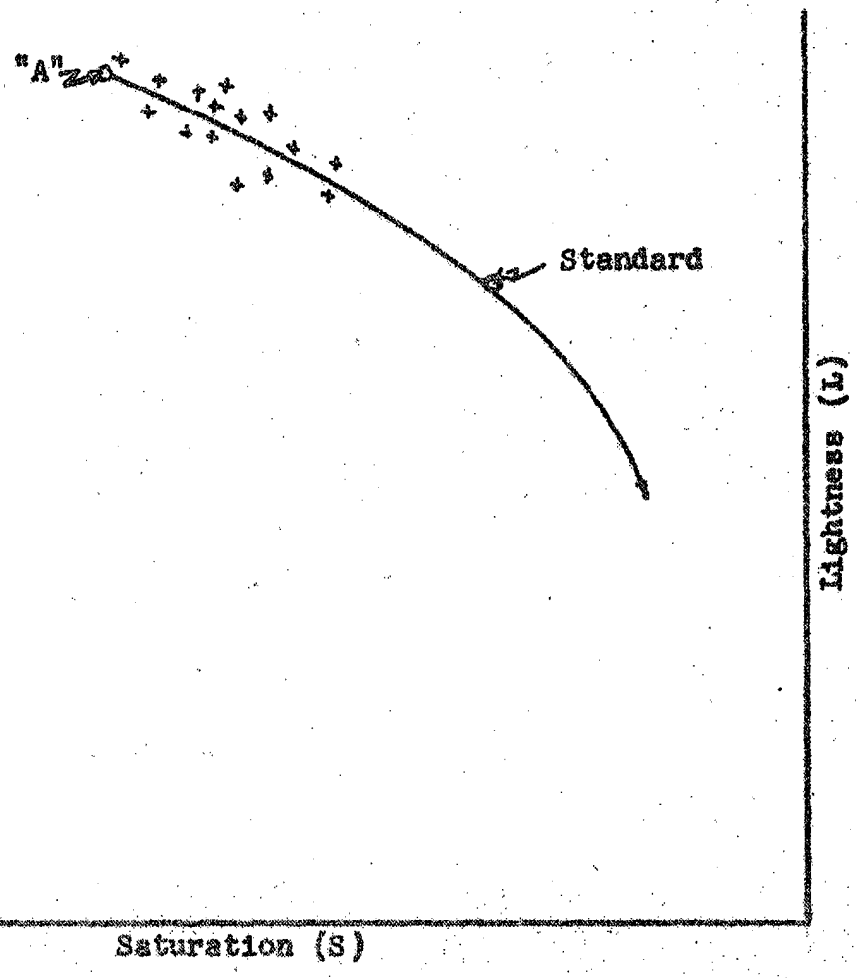
In this case two white pigment dispersions "A" and "B" have been mixed with a color pigment dispersion "C" and the locus of the colors obtained plotted as a lightness vs. saturation curve. Inspection of these curves indicates that the primary color difference induced in blended colors will be in the region of near-whites and pastel colors, i.e., in blended colors containing a large percentage of the white. Since the differences in masstone lightness and saturation each contribute to the difference between the curves of Figure XXXVII, any corrective measures must adjust both masstone lightness and saturation.

Inspection of the masstone data accumulated by Ajax indicated that their production increased in lightness when the saturation (yellowness) increased. (Note Figure XXXVII.) The general

Figure XXXVII

Variation of Masstone Lightness with Saturation

TiO_2 Dispersion - Ajax Plant

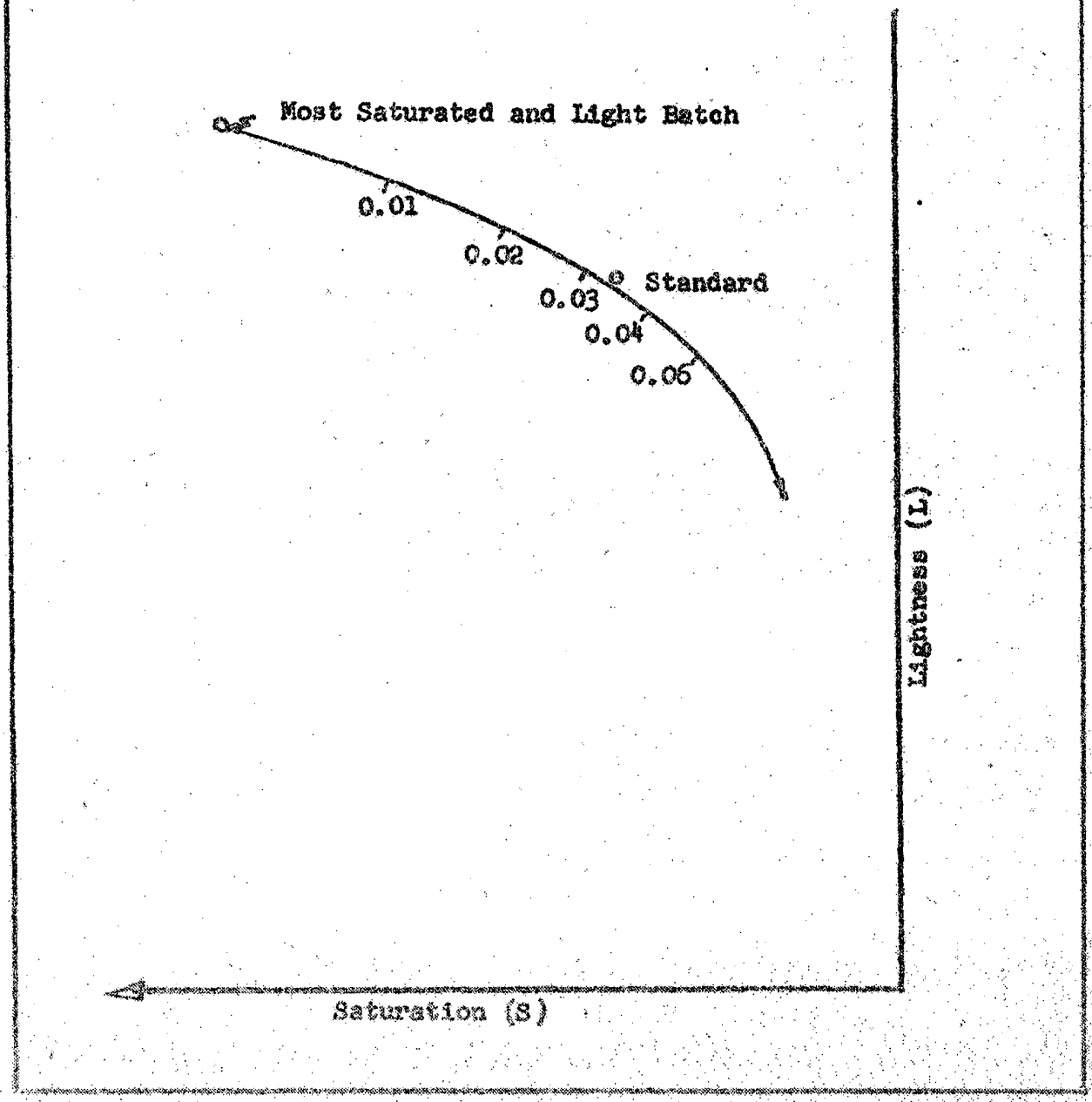


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slope of the locus of these points corresponds favorably to the curve obtained when adding small amounts of a blue hued black (such as W-230) to a white pigment dispersion. The addition of black pigment dispersion can be governed by a calibration curve similar to that of Figure XXXVIII where the most saturated batch is adjusted with varying amounts of the black pigment base.

Figure XXXVIII

Calibration Curve - Adjustment of White Pigment Dispersion



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While the effects of hue, saturation and masstone lightness differences of black pigment dispersions will have an effect in the dark color range similar to that of white pigment variations in the light color range, substantial correction beyond more uniform dispersion techniques to obtain similar masstone lightness from lot to lot may not be necessary in view of the increased visual tolerance to color differences in the low lightness area of the color solid.

The color characteristics of tinting bases may be controlled by utilizing the techniques detailed in the previous discussion. Briefly, adequate control of the color characteristics of pigment dispersions requires masstone lightness and saturation control using the techniques of the "neutral gray" standardization procedure as well as the current tinting strength standardization procedure. This will require a change in our current pigment procurement procedures to institute a masstone lightness control as well as the currently proposed strength and color limitations. The institution of stringent masstone lightness control is of particular importance for these colors whose saturation increases rapidly as the masstone lightness of the color is approached (note Figure XXXIX). In this case, the "neutral gray" standardization procedure, which can normally be used for the adjustment of masstone lightness differences, will result in a loss of saturation in fixed formulation colors made from essentially 100% of the adjusted colorant. Typical examples of colorants requiring close masstone lightness control before "neutral gray" adjustment are the various Cadmium Reds and other pigments giving Type 2 curves as shown in Figure XIV.

The number of pigments requiring this tight control of masstone lightness is limited. Most pigments have a Lightness vs. Saturation curve similar to Figure XL, indicating that adjustment of the masstone lightness can be made over relatively broad limitations without affecting the saturation of the colors formulated at or near the 100% colorant level.

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Figure XXXIX

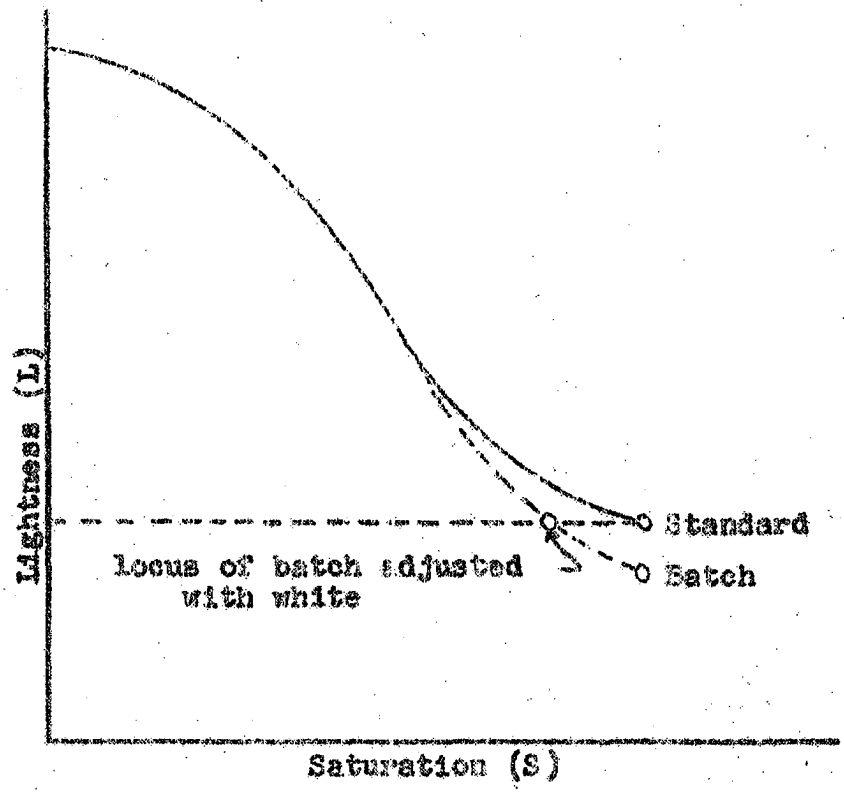
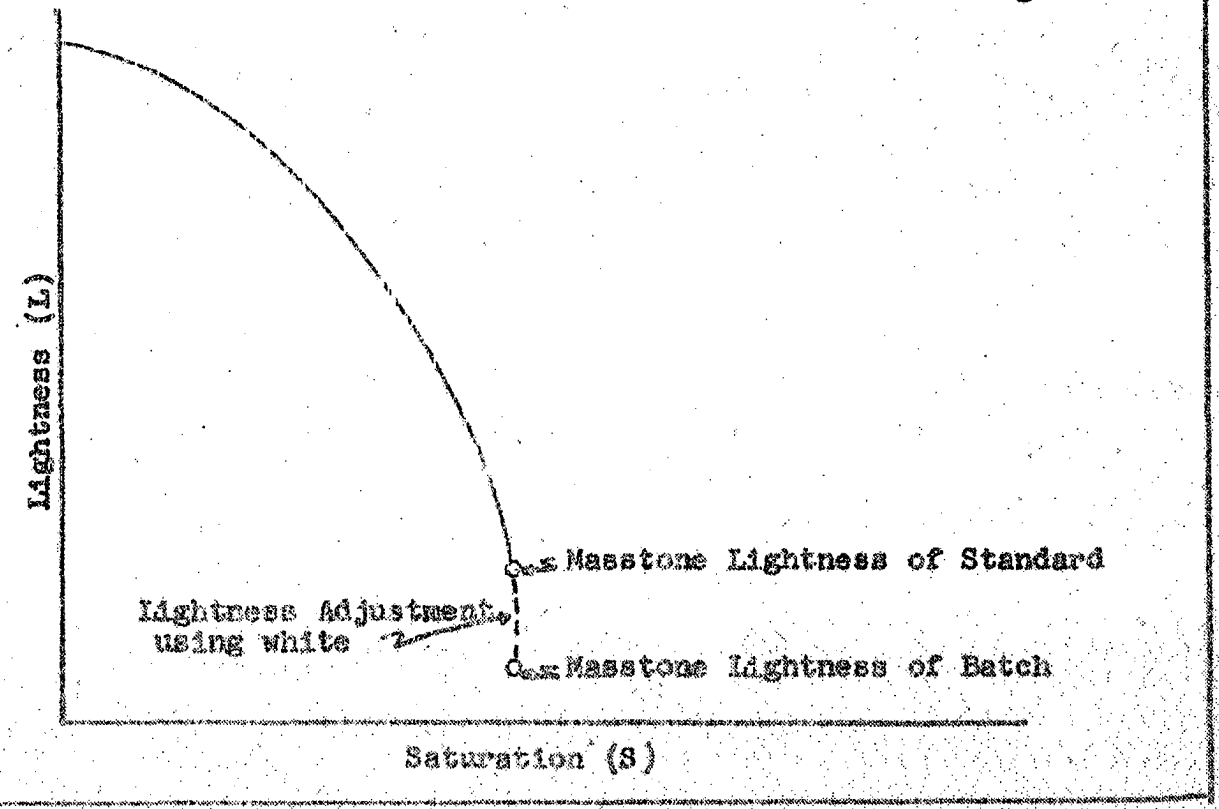


Figure XL



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The Dispersion of Pigments

The dispersion of pigments can be responsible for much of the lot to lot color variation inherent in our production. As was mentioned earlier (pg. I-2), the basic color (i.e., red, green, blue or yellow) produced by a pigment is due to its molecular structure. This color can be modified to a limited extent by variations in the particle size or particle size distribution of the pigment resulting from variations in the dispersion of the pigment. Current dispersion practice considers the attainment of a certain degree of "fineness" as a measure of the degree of dispersion of the pigment. The fineness gauge essentially measures the size and concentration of the abnormally large pigment particles in the film but does not assess the particle size or particle size distribution of the bulk of the pigment which controls the lightness, hue and saturation characteristics of the dispersion. To understand what is actually taking place during the course of the dispersion, it is necessary to "track" the dispersion process for a colored pigment using the principles of the Mathematical Color System and the Vectoral Coordinate System to determine what is taking place. (Note Figure XLI.)

As the dispersion process commences, there is a real change in hue and an increase in saturation. This change is due to the rapid dispersion of the agglomerated pigment particles which results in a change in the particle size distribution toward the fundamental particle size of the pigments. This change in particle size distribution shifts the reflected color hue and saturation toward the true hue and saturation of the pigment.

This change in hue and saturation will continue until an equilibrium point is reached where the particular process will not produce any further dispersion in the specific formulation. The dispersion cycle and color characteristics of a pigmented dispersion at this point of equilibrium dispersion are dependent upon the composition of the pigment base. Close adherence to the pigment packing principle of pigmented base formulation, where applicable, will normally result in the development of optimum dispersion pigment color characteristics at the most economical rate of dispersion.

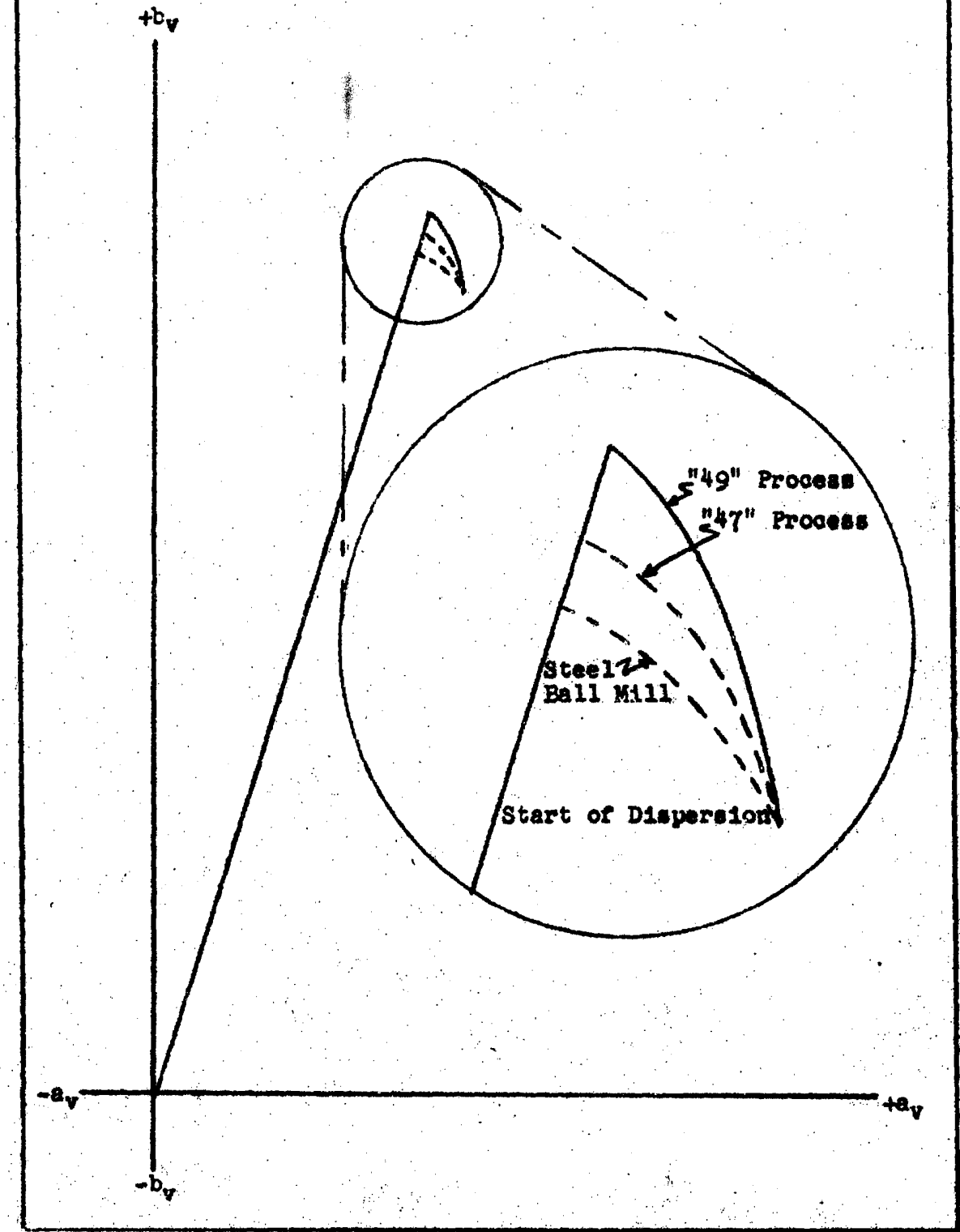
Continuation of most dispersion operations beyond the point of equilibrium will result in no noteable change in the real hue of the dispersion, but a reduction of the saturation characteristics of the dispersion will be apparent. This reduction in saturation is attributable to the contamination of the pigment dispersion with steel ground from the shell, balls, or discs involved.

This type of contamination is virtually non-existent in "49 Process" and pebble mill dispersions. Steel contamination is a factor in "47 Process" and even more so in steel-lined steel ball mill dispersion processes. It is possible to overgrind dispersions by these methods until the color produced is definitely "dirty". Visual color comparison will not permit the determination of the point of equilibrium because this steel contamination is visually interpreted as a change in hue and saturation. In certain colors, the effect of steel contamination may give the appearance of further color development.

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Figure XLI

Color Pigment Dispersion - Mathematical Interpretation
White "Let Down" Computed to Constant Lightness



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Since steel contamination is a factor in the "47 Process" and steel mill dispersions at all phases of dispersion, it is apparent that the hue and saturation increase found in the pigment dispersion prior to the point of dispersion equilibrium will be somewhat reduced by the steel contamination inherent in these processes. The broken curves in Figure XLI illustrate the effect of steel contamination in these processes on the reduction of the saturation development in the early stages of dispersion.

Evaluation of a variety of pigment dispersions indicates that these pigment dispersions have not reached the point of equilibrium dispersion. Operation at the point of equilibrium dispersion offers several theoretical advantages.

1) The maximum saturation of the pigment will be obtained. This will result in an extension of the area in which the color can be utilized.

2) The influence of the inherent lot to lot variables such as temperature, resin wetting and viscosity on the lot to lot color reproducibility will be diminished. The previous discussion of pigmented base standardization has emphasized the need for color reproducibility, particularly in masstone lightness and hue.

3) Improved dispersions normally result in a higher tinting strength.

In many cases, the overall color effect resulting from a change in the dispersion cycle to the level of equilibrium dispersion may not be commercially significant, but it is impossible to ascertain this fact until after the evaluation has been made. In development work, this technique has been used to determine the effect of changes in formulation on the dispersion of a pigment. The use of these techniques in development work has resulted in the determination of qualitative data which could not be otherwise obtained.

Evaluation of Pigments

The evaluation of pigments from new suppliers is currently dependent upon visual interpretation of paste rub-outs, let-down panels or formulation of finished products from the color pigmented bases produced from these pigments.

This visual interpretation has many limitations which seriously restrict the judgment of the visual observer with respect to the acceptance or rejection of a given pigment. The non-linearity of the visual response of the eye to color is the main reason for this lack of visual judgment realiability. The visual color system shows marked variation in the visual hue of a pigment with changes in lightness and saturation. In the region of blue pigments, for example, visual comparison of two pigments having the same Vectoral Coordinate System hue but differing in saturation, the more saturated pigment is usually reported as having a "red tone" and the less saturated pigment as having a "green tone". (Note Figure XLII.)

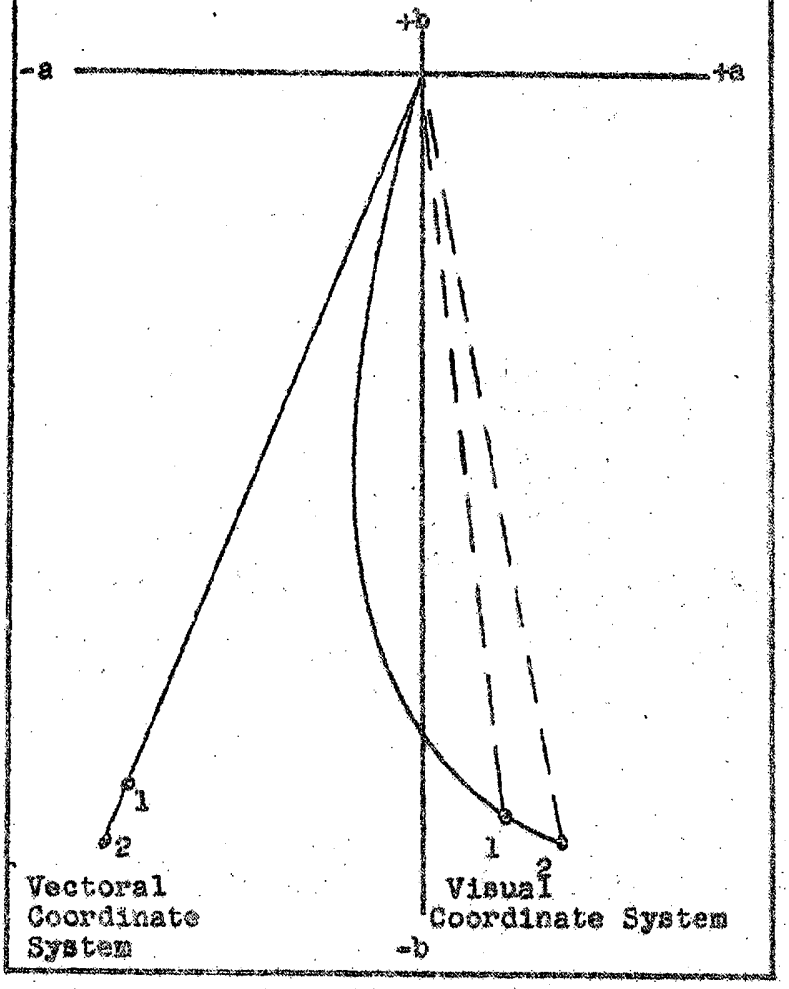
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The maximum saturation curve, obtained when a color is let down with white, is the key to the evaluation of pigments for it allows a quick decision as to the range of color which can be formulated with the pigment in comparison to the range of color available with current pigments or pigment combinations of the same hue.

The Mathematical Color System allows the calculation of the maximum saturation vs. lightness curve obtainable with a given pigment in the form of a pigmented base. The application of this system to the problem has several advantages over the visual interpretation method:

1. Under the VCS, the hue of a single color pigment add to white (neutral) pigment remains constant at all conditions of lightness and saturation, allowing an accurate comparison of pigment hue to be made regardless of differences in strength and saturation.

Figure XLII
Visual Misinterpretation of Pigment Hue



2. The preparation of four panels will provide sufficient information about each color pigment dispersion to completely define the strength and the maximum saturation vs. lightness curve. The comparison of this curve with a similar curve derived from the standard pigment will then allow an accurate decision on the feasibility of utilizing this pigment in color formulation.

3. Pigments and color pigmented dispersions which vary widely in strength can be accurately compared for color gamut in the same manner.

There are two basically different types of saturation vs. lightness curves found in the evaluation of colored pigments. The first type occurs when the masstone lightness of each of the evaluated pigment dispersions is virtually the same. This type of curve is usually found when potential suppliers submit pigment offerings

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corresponding to existing standard pigments. (Note Figure XLIII

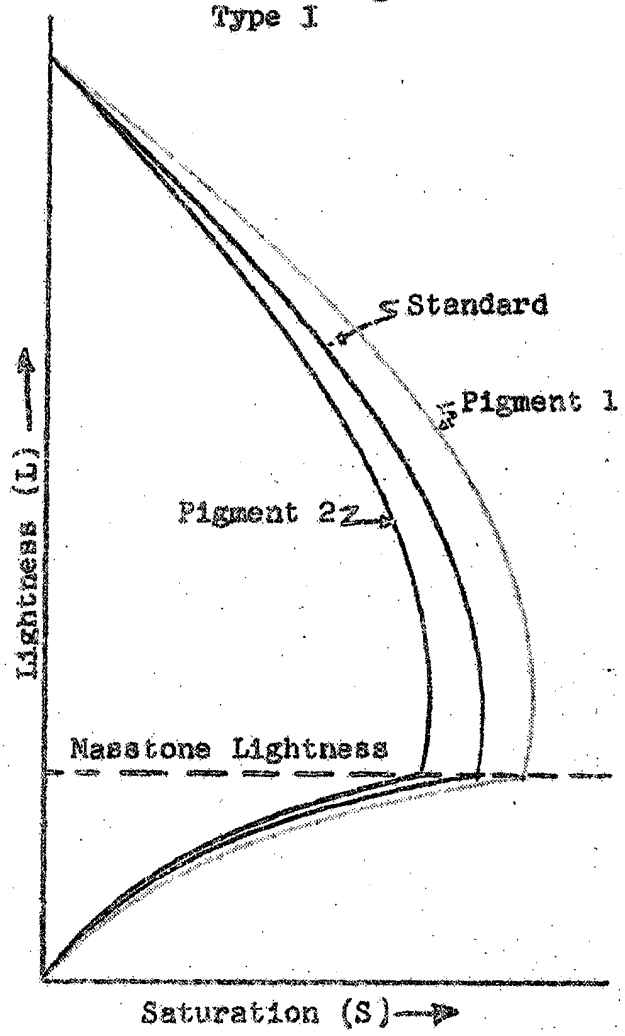
Any pigment which is to replace or supplement a standard pigment must match the pigment in masstone lightness in order to be usable in the Mixing Machine Program. (Note the previous discussion on pigment dispersion standardization.)

The interpretation of these curves is relatively simple. If the test pigment dispersion saturation vs. lightness curve indicates greater saturation than the curve obtained with the standard pigment dispersion, the test pigment will make all the colors that can be made with the standard pigment plus colors of greater saturation whose locus lies between the standard and test pigment saturation curves.

If the test pigment dispersion saturation vs. lightness curve is identical with that of the standard pigment dispersion, the test pigment will make all of the colors that the standard pigment can make.

Figure XLIII

Saturation vs. Lightness Curves
Type I



The saturation vs. lightness curve for the test pigment dispersion may show a reduced saturation when compared with the curve of the standard pigment. This indicates that the test pigment is not desirable in that it cannot be used to match those colors whose locus lies between the test and standard pigment curves. This pigment should be rejected as a potential alternate source of supply or replacement for the standard pigment.

The second type of saturation vs. lightness curve (Note Figure XLIV) is usually found when a new pigment offering is compared to existing pigments currently used in the formulation of colors in the hue range of the new pigment. In this case the masstone lightness

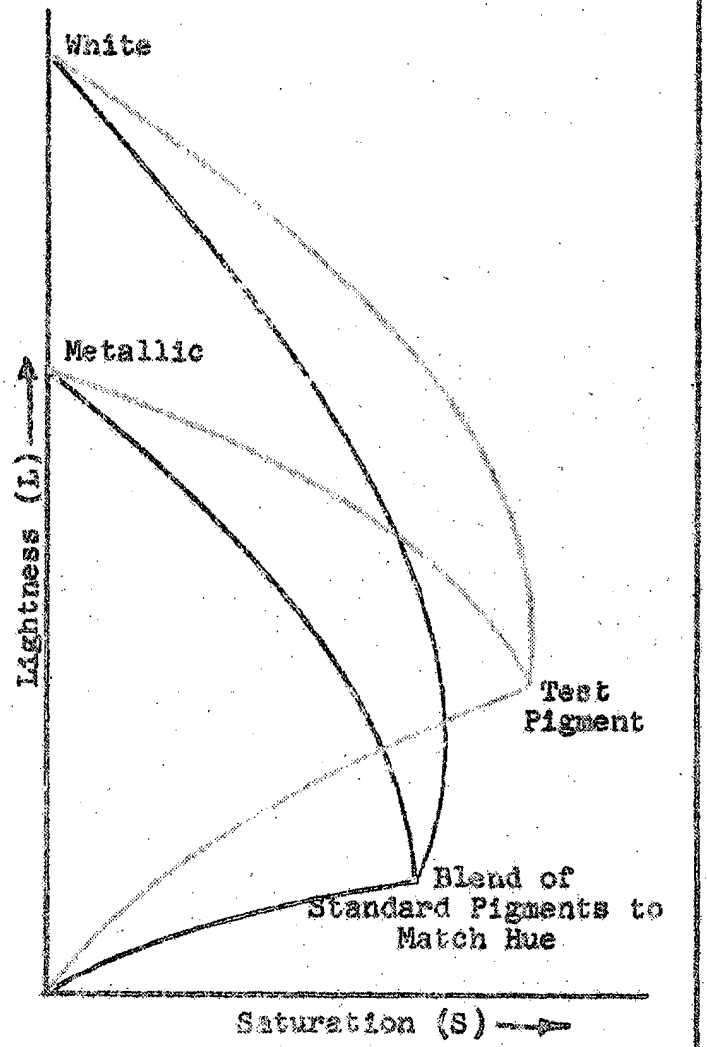
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of the new pigment will probably differ widely from the blend of the current pigments used to obtain maximum saturation at the hue of the new pigment. If preferred, the new pigment can be compared in both metallic and non-metallic formulations for saturation vs. lightness curves.

Figure XLIV

Saturation vs. Lightness Curve

Type II



Inspection of these curves indicates that the test pigment dispersion (green curves) has greater saturation than the standard pigment dispersion blend (red curves) in the light color range and less saturation in the dark color range. The acceptability of this pigment (economic reasons excluded) hinges on the pattern of usage of the existing or standard pigment blend.

If the standard pigment dispersion is used primarily as a white tint the test pigment dispersion will provide greater saturation latitude in this region or in high metallic color formulations. Conversely, if the standard pigment dispersion is primarily employed in the dark color region, or in dark metallic color formulation it provides a greater degree of saturation latitude in this region than the test pigment. The test pigment is therefore not a satisfactory substitute.

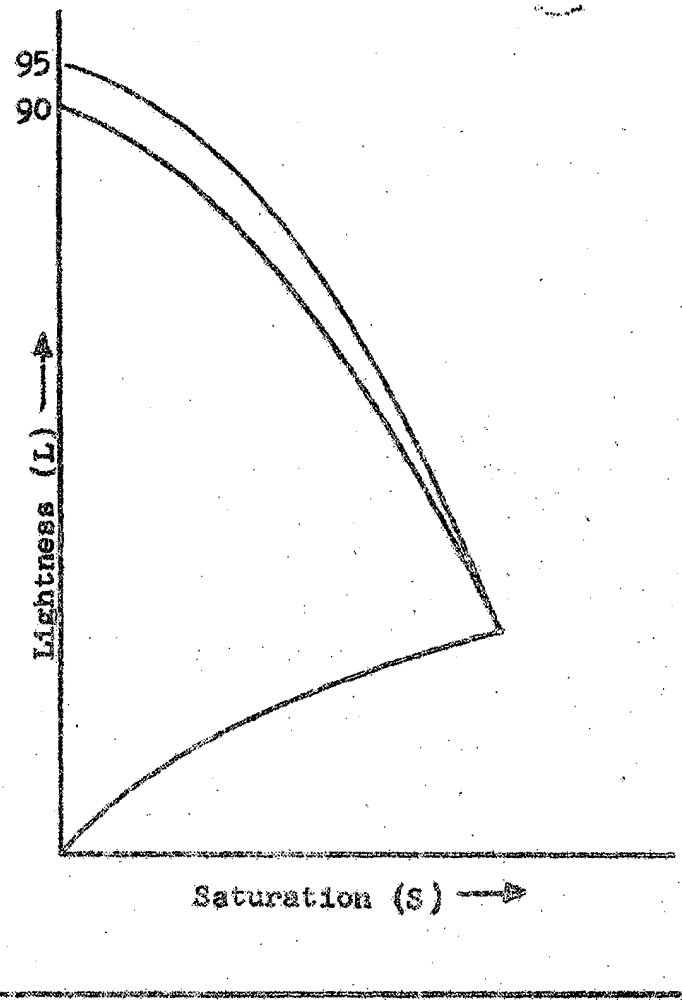
Since the "two-tone" of metallics is an important consideration, several blends should be made comparing the test pigment and the standard pigment blend for "two-tone" at constant lightness prior to acceptance or rejection of the new pigment.

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One factor often overlooked is the extension of the color range offered by improvements in the manufacture or dispersion of neutral pigments. A lighter white (Note Figure XLV), a lighter aluminum, or a darker black significantly increases the range of saturation which can be obtained with existing color pigments. This effect is greatest in the light color range (in the specific case of the improved white) but continues until the masstone of the colorant is reached.

Figure XLV.

Effect of Lighter White on Saturation



The effect of relatively small changes in the masstone lightness of a neutral pigment on the saturation is readily explained. A lighter white requires more of a color pigment dispersion to reach a given lightness than was required with the darker white. The use of more colored pigment in the white/color blend results in a greater saturation at this level. The pronounced effect of small masstone lightness changes for the neutral colorants on the saturation vs. lightness curve explains the need for close control required in the production of neutral colorants for the various mixing machine lines.

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