Color Radiography

A Thesis

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ABSTRACT

A radiograph is usually "read" by visual observation and interpretation of shadings on a photographic film that has been exposed to x- or gamma radiation. Better results may be obtained if color could be incorporated into the radiographic process. This is a direct application of the physical fact that the human eye is more sensitive to changes in color than to changes in shading. Theoretically, more or better information could be obtained from a radiograph simply by taking advantage of the physical characteristics of the detection device--the human eye.

It is the purpose of this thesis to investigate methods of adding color to radiography. A survey of previous methods is presented and an attempt is made to incorporate information derived from them into a simple method to obtain color radiographs. Examples of the application of the technique are presented.

INTRODUCTION

Nondestructive testing has been defined as a process "to detect internal and concealed defects in materials using techniques that do not damage or destroy the item being tested."[1] Some of the more familiar techniques include ultrasonic testing, dye penetrants, eddy current testing, and radiography.

The most prevalent use of radioisotopes in American industry today is radiography. This is a process in which a shadow image of the test specimen is recorded on photographic film. By observing the shading on a radiograph, it is possible to determine a change in the density or thickness of the test specimen. To aid in understanding this process, a short discussion of radiography will be presented here.

Electromagnetic radiation in the form of x- or gamma rays is emitted from a source. These rays penetrate the specimen and are recorded on film. (See Figure 1-1)

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[1]Harry D. Richardson, Industrial Radiography Manual, U.S. Atomic Energy Commission Contract No. AT-40-1-3122 (Baton Rouge, Louisiana, 1964), p A-7.

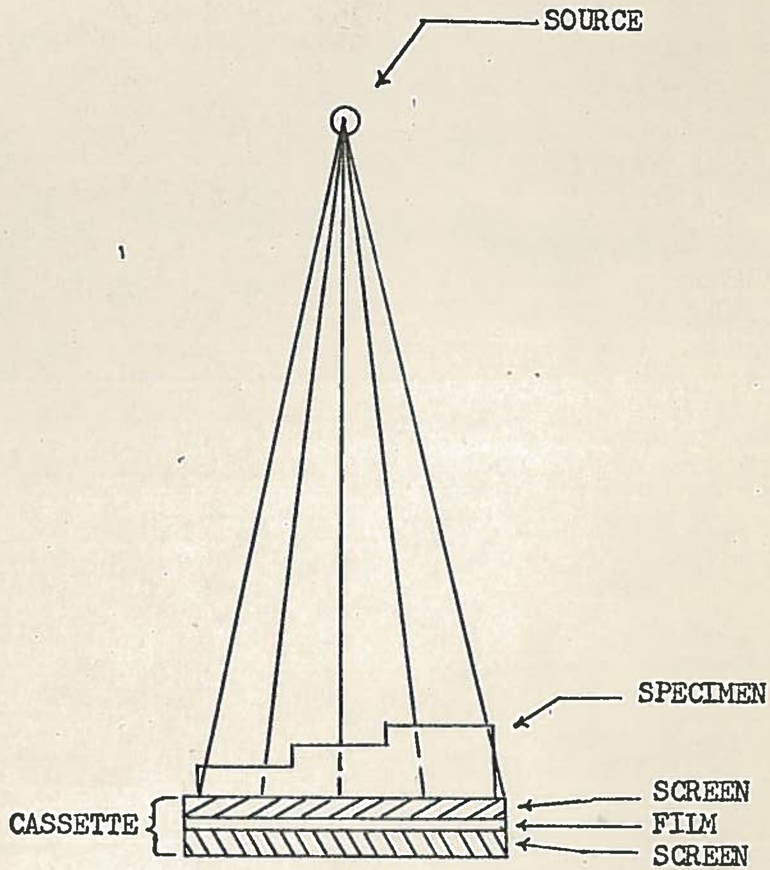


FIGURE 1-1

TYPICAL RADIOGRAPHIC ARRANGEMENT

The amount of radiation reaching the film is given by the equation, $I = I_o e^{-\mu_1 t}$.

I_o is the intensity reaching the film if no specimen were present.

I is the intensity reaching the film with a specimen present.

e is the natural logarithm base.

μ_1 is a constant for a given energy and material and is referred to as "linear absorption coefficient."

t is the specimen thickness.

μ_1 is usually expressed in the form $\mu_1 = (\mu_1/\rho)$. (μ_1/ρ) is referred to as mass absorption coefficient and carries the units of cross sectional area per unit mass. ρ is the density of the material being tested.

From the above relationships, it can be seen tha the amount of radiation transmitted through a specimen is a function of the incident radiation and the thichness and density of the test specimen.

The amount of radiation being transmitted is of great importance in radiography. In effect, radiography is simply a measure of this quantity. Usually this measurement is achieved by the use of photographic film. On the other hand, phosphor screens are also commonly used as detection devices. Since film is the main agent of detection in radiographic work, it is necessary to have some understanding of the principles of film and film development to completely understand the entire radiographic process.

Film is composed of a silver halide emulsion deposited on a transparent base material. Generally, the halide used is bromine. The silver halide grains of the emulsion are activated through the absorption of energy and reduce to metallic silver, dark brown in color, during development procedures. The extent of activation, and therefore the shading on the rediograph, is dependent on the amount of radiation absorbed by the film. It is therefore inversely proportional to the amount absorbed in the specimen. Through this process, a photographic negative of the specimen is obtained.

If a flaw exists in the enternal structure of the specimen, it has the effect of changing the density of that cross section. For example, if an air pocket is produced in casting, the density at this point would be considerably lower than at an adjacent area at which no void was present. Consequently, less of the incident energy would be absorbed at this cross section. The resulting radiograph would exhibit a darker area corresponding to this void. For illustrative purposes, an example of such a specimen and the resulting radiograph are shown in Figure 1-2.

For complete information on the technicalities involved in obtaining a good radiograph, it would be advisable to consult a complete radiographic manual such as the one by Richardson.[2]

There are many variables involved in this process, and only the basic ones will be summarized here. The wave length of the incident beam determines its penetrating power. The energy of the penetration rays are

[2] Industrial Radiography Manual.

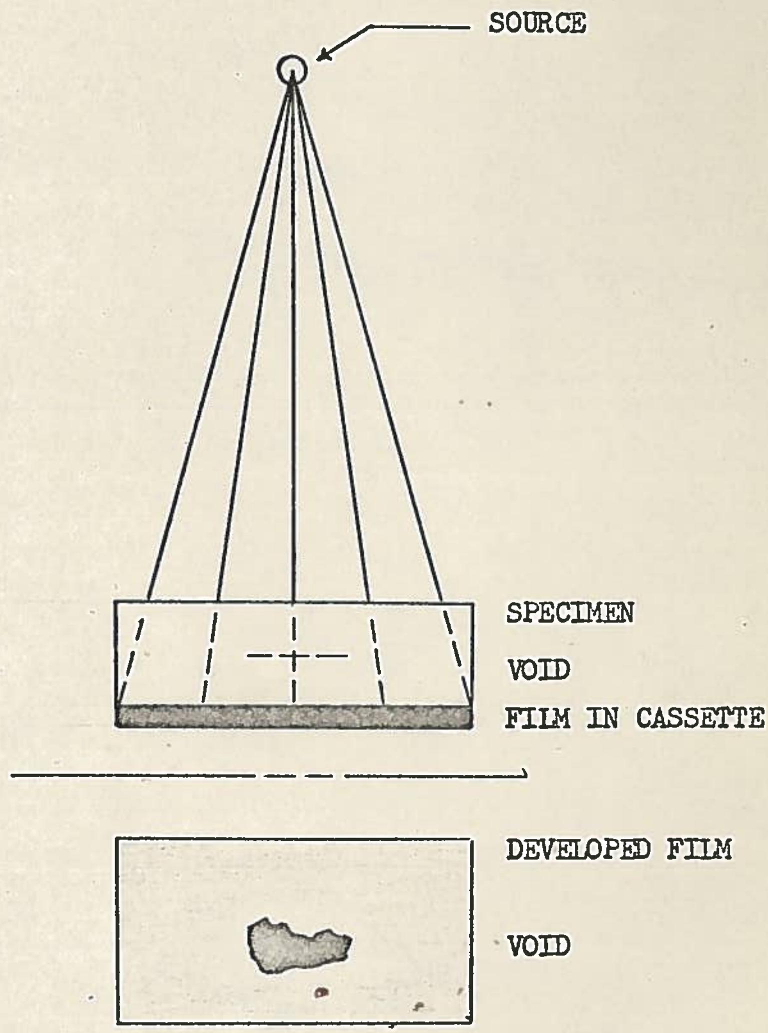


FIGURE 1-2

SPECIMEN AND RESULTING RADIOGRAPH

directly proportional to the frequency. It is therefore inversely proportional to the wave length. In these relationships, the constants of proportion are the speed of light and Plank's constant. These relations are mathematically presented as:

$$E = h\,f$$

$$f = c/\lambda$$

$$\therefore E = \frac{hc}{\lambda}$$

E is the energy.

h is Plank's constant.

f is the frequency.

λ is wave length.

c is the speed of light.

Substituting numerical values yields:

$$E \cong \frac{(6.6 \times 10^{-34}\ \text{J s})(3 \times 10^{8}\ \text{m/s})}{\lambda\ \text{m}}$$

$$\boxed{E \cong \frac{1.98 \times 10^{-25}}{\lambda}\ \text{Joules}}$$

Where 1 Joule = 0.7376 ft. lb_f.

The wave length is controlled in radiography by choice of voltage in the case of x-rays or choice of source in the case of gamma rays.

The intensity of exposure is dependent on the quantity of radiation and the time of exposure. This factor is referred to as "exposure" and is expressed in milliampere seconds for x-ray machines. In other words, similar results could be obtained if the amount of radiation were doubled and exposure time simultaneously cut in half.

Geometric considerations also are of great importance. To obtain results with minimum distortion, it is necessary to keep the distance between the subject and film as small as possible while keeping the distance between the source and subject large enough to insure uniform exposure of the entire subject.

Other factors that influence the radiograph to varying degrees are: choice of film, film developing techniques, and use of screens.

Radiographs, in the sense of the above discussion, are "read" by observing the shades of gray that appear on the exposed film after development. If this difference in shading could be transformed to a difference in color, the result would be a "color radiograph." Color radiography will be defined, therefore, as a process in which differences in density or thickness of the test specimen appear as differences in color on a radiograph of that specimen. It should be immediately pointed out that in no way does color radiography try to reporduce the naturally occuring color of an object. Only color contrast at interfaces is of concern.

It is suggested that perhaps later work in this field will be directed toward correlation of color obtained on the radiograph to some physical property of the specimen. At that time it may become possible to identify materials by their color on a radiograph. This remains far in the future and can be accomplished only after the basic techniques of color radiography are mastered.

Light and Color

It is a physical fact that the eye is more sensitive to changes in color than to changes in shading. Light has three basic properties that are discernible by the human eye. These are hue, brightness, and density. Hue refers to what is generally called color. In other words, the eye is able to distinguish between red, blue, green, etc. Brightness is a term referring to the intensity of light reaching the eye. This means that we are able to distinguish between bright red and dull red. Density refers to the amount of hue present. This is what we speak of in describing dark or light hues.

The detection of these three properties by the eye is very complex owing to both biological reasons and their interdependence on each other. These factors will now be briefly looked into.

The biological structure of the eye is extremely complex and its operation is even today not fully understood. Since this process is of only secondary importance to this thesis, only a very qualitative and general discussion will be presented.

Light enters the eye and is focused on the retina by the lens. The retina is composed of approximately one million nerve fibers. These fibers come together to form the optic nerve. Also present in the retina are rods and cones. These number 125 million and $6\frac{1}{2}$ million respectively. Considering only the numbers involved, it is obvious that each nerve ending contains several cones and an even larger number of rods.

The rods are the primary agent for detection of intensity variation. The cones function over a more limited range and act as a complement to the rods in the differentiation of color. This process can best be explained by the use of an example. The following discussion also points out the interdependence of hue, shading, and brightness.

When the intensity of light is low, dull, the eye is only able to distinguish outlines of objects. No color is observed. An obvious example of this occurs in nature at night. If two cars, one red and the other blue, were parked next to one another at night, one could only tell their model from observation of their respective shapes. Their identification by color would be impossible. When the light becomes more intense, brighter, colors are observed by the eye. While in the former case only the rods were being utilized, now both the rods and cones are functioning. If a still greater intensity of light were incident on the cars, such as illumination with a spotlight, they could be made to appear in several hues different from their true color. For example, the red car can be made to appear orange, brown, or yellow. When this happens, the range of the cones has been passed and their effectiveness greatly decreased.

From the above discussion, we can deduce that the sensitivity of the eye as a detection agent is greatest in the limited range of the cones. In this region we are able to take advantage of a biological fact to detect all three basic properties of light; color, brightness, and density.

Since the production of color is of central importance to this thesis, it is imperative that a discussion of the physical properties of light with regard to color now be presented.

The region on the electromagnetic spectrum lying between 10^{-6} and 10^{-7} meters in wave length is the only portion of the spectrum to which the eye is sensitive. For this reason, it is commonly referred to as "visible light." In this particular range, however, the eye is very sensitive to small changes in wave length. If this region were further divided into smaller sections, regions of the six primary colors could be observed. The entire spectrum with emphasis on this region is diagramed in Figure 1-3.

Basically, the only difference between different color lights is their wave lengths. This is the principle that is observed in the use of the refraction crystal. Here light of differing wave length is deflected at different angles. When all wave lengths (white light) are incident on the crystal, the entire color spectrum is reproduced on a screen.

With the combination of certain primary colors, almost any desired color can be achieved. These colors have been referred to as the basic colors.

Light rays of varying wave lengths, and therefore colors, are combined in an additive process to form a color that is different from any component part. If all wave lengths are present in the combining process, the result will be white light. Color, in the usual sense, is defined

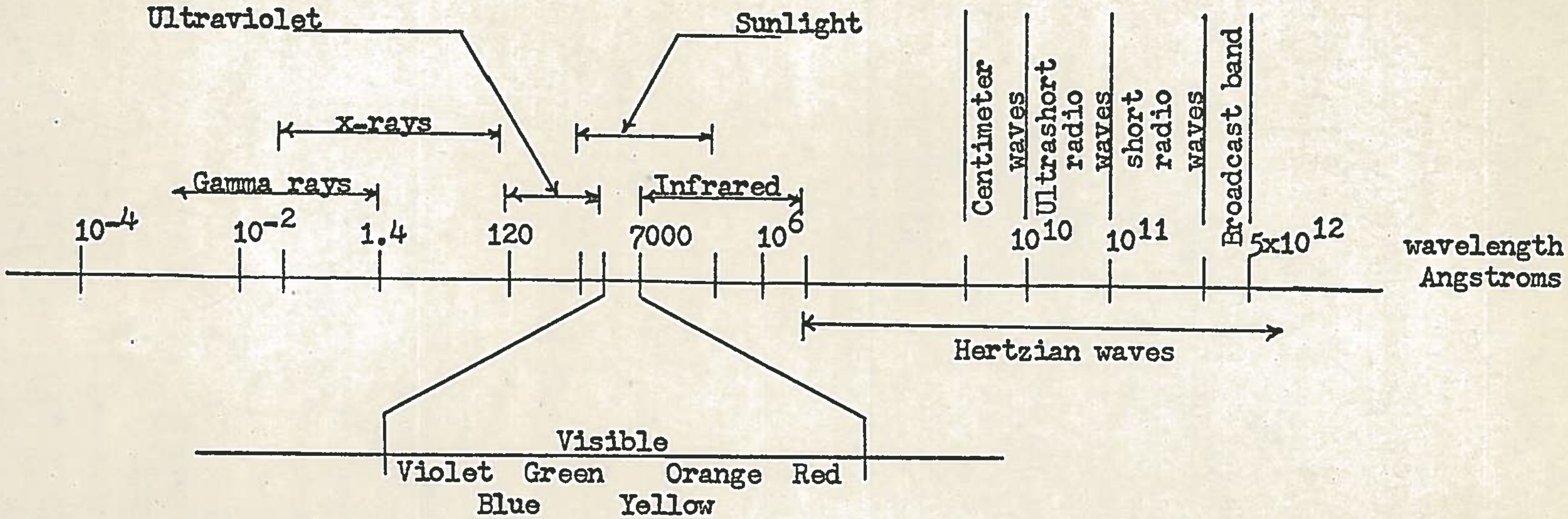


FIGURE 1-3

THE ELECTROMAGNETIC SPECTRUM

in a slightly different manner. In fact, this definition of color is actually the exact opposite of process by which light hues are identified. When light is incident on a body, some of it is absorbed--the remainder being reflected. It is the reflected portion that is visible to the human eye. An object's color is thought of as a combination of the hues being reflected. From the true definition of color, an object is actually all colors but the ones being observed. This process of light reflection is referred to as a subtractive process as compared to the additive process of light combination.

It has been found that it is possible to reproduce any color by the combination of three basic colors. This process consists of taking colors from the two extremes of the visible light portion of the electromagnetic spectrum and one from the middle section. In additive color production the hues usually chosen are red, green, and blue. By combining a hue from one extreme with the central hue, it is possible to produce all hues between those chosen. Now, using the other extreme hue with the central one, it is possible to produce the other half of the spectrum. Using all three simultaneously produces white. Consequently, we have produced all possible colors using only three basics.

Figure 1-4 shows how the three basic colors of red, green, and blue can be mixed in additive process.

Additive and subtractive processes are related through the concept of complementary colors. Any two colors that combine to produce white light are, by definition, complementary. A color produced by an additive

FIGURE 1-4

ADDITIVE COLOR MIXING

process is the complement of the color produced through a subtractive process of the same basic components. The basic colors in additive processes have been listed as red, green, and blue. In subtractive processes, the basics are the complements of these. They are cyan, magenta, and yellow respectively.

Cyan is the combination of blue and green; thus the complement of red. In a similar fashion, magenta is a combination of blue and red and the complement of green; and yellow is a combination of red and green and a complement of blue.

The subtractive process is summarized in Figure 1-5 and complementary colors in Figure 1-6.

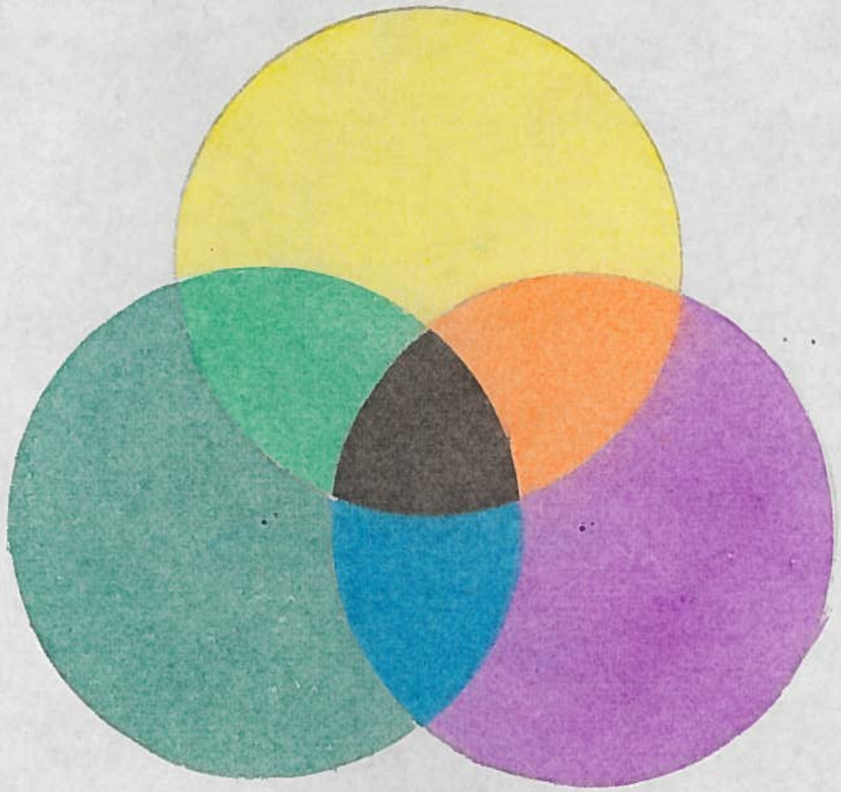
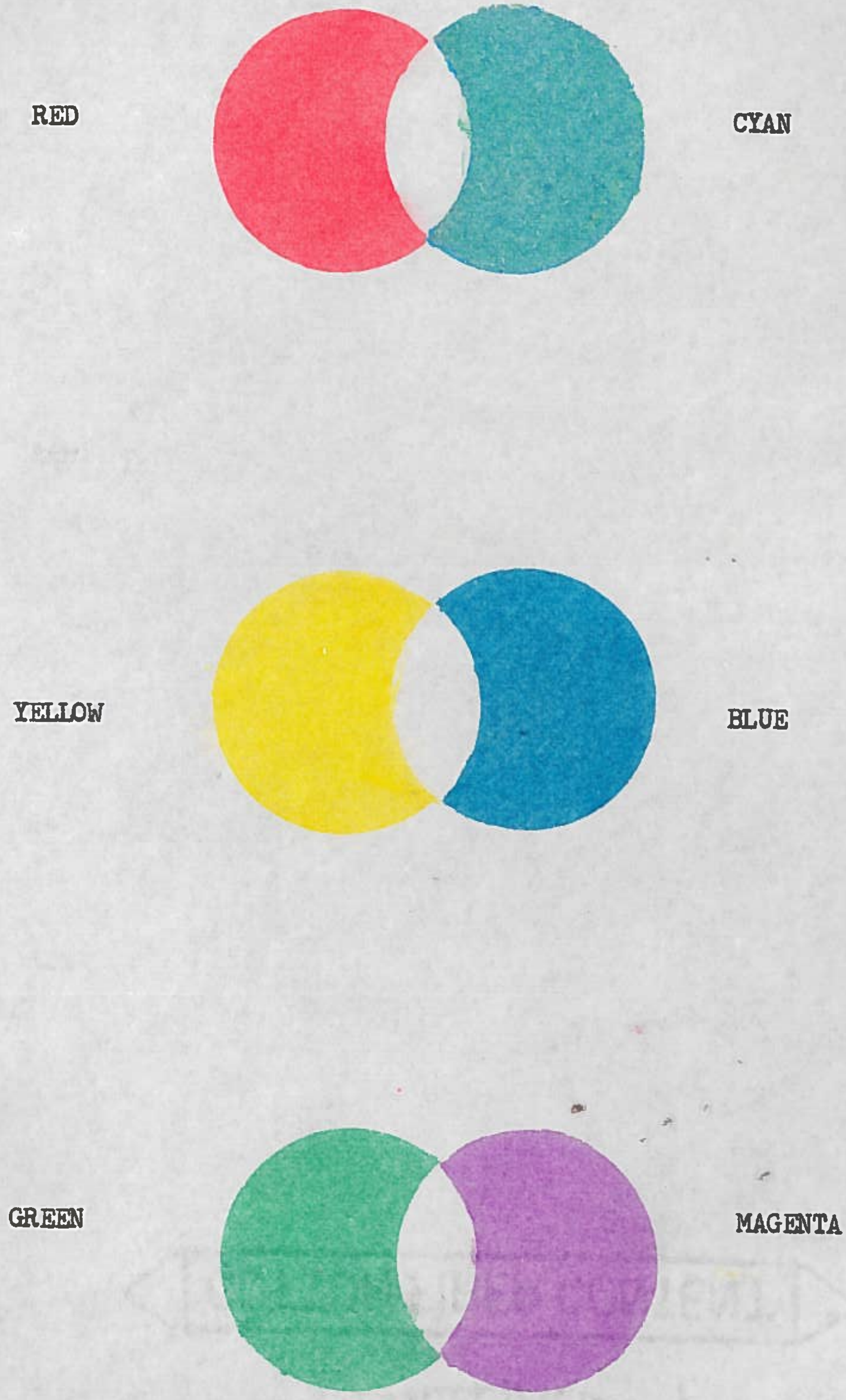


FIGURE 1-5

SUBTRACTIVE COLOR MIXING

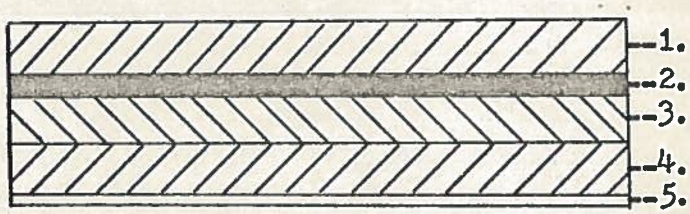


FIGYRE 1-6

COMPLEMENTARY COLORS

Color Film

It has been shown how the three primary colors of red, green, and blue can be mixed to form any desired hue. Color film incorporates this principle fcr its operation. All color film is made in the same basic pattern. There exists within the film three separate emulsion layers sensitive to blue, green, and red light respectively. Sandwiched between the blue and green layers is a yellow filter. This arrangement, referred to as a tripack, is schematically shown below.



1. Blue Sensitive Layer
2. Yellow Filter
3. Green Sensitive Layer
4. Red Sensitive Layer
5. Transparent Base Material

FIGURE 1-7

TRIPACK COLOR FILM

As light enters the film the blue sensitive layer is activated by any blue wave length present. The purpose of the filter is to stop any further penetration by blue light. This process is sufficiently explained by remembering that blue light combined with yellow light yeilds white light. As a consequence, only green and red wave lengths are allowed to penetrate past the filter. Any green or red wave lengths are subsequently recorded on their respective emulsion layers.

In the development process, the dyes in the three layers are activated to display their respective colors. At this point, a distinction is made between color positive and color negative film. Color positive film is the type designed to be viewed by projection. Of general reference here is slide or movie film. Color negative film is, on the other hand, translucent film whose primary purpose is to produce color prints.

In color positive film development, the dyes formed in the initial development are allowed to remain. All unexposed portions are then removed. In this process, the true color is present on the film after development.

In color negative development, the image formed in the first development is removed by bleaching. What remains is an image in the complementary colors of true reproduction. In the re-exposure during the printing process, another reversal takes place with true color reappearing on the final print.

In the experimental work described here, only color positive, or transparent, film was used. The reason for this is simply one of economics. Color positive film requires fewer developing steps, therefore its use is cheaper and quicker. It seems reasonable to assume that comparable results may be obtained if color negative film is used.

History

The change in color of certain chemicals from the exposure and absorption of radiation has been used as a method of dosage determination since the beginning of the twentieth century. With the development of radiography techniques, scientists have been striving to link these two areas in the production of color radiographs. Significant contributions were first made only in the last fifteen years.

In 1951, Donovan[3] outlined a method for indirect color radiography. His work was based on the fact that the degree of hardness of an x-ray has a direct effect on the resulting radiograph. The degree of hardness is in turn a function of the applied voltage, in the case of x-rays, or of the source in the case of gamma rays.

Donovan suggested that three radiographs be taken of the subject at varying voltages. The radiographs obtained are then processed in the usual fashion. In doing this, the three exposures emphasize different areas of the subject. Being a Doctor of Medicine, Donovan's work was primarily in the field of medical radiography. Consequently, his examples were of human tissue and bone. The radiographs taken at low voltages emphasize the tissue while those at high settings are primarily for bone.

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[3] G. E. Donovan, "Radiography in Colour," The Lancet, (April 14, 1951), pp 832-33.

Donovan suggested that three radiographs be taken at high, medium, and low voltages. These transparencies are then projected simultaneously onto a screen with lamps of the three basic colors; red, green, and blue. He reported better success if the radiographic positives are used in place of the negative. If a print of the composite is desired, it can be obtained by standard photographic processes. Donovan suggested simply making exposures onto color photographic paper. An example of this would be projecting the low voltage exposure with green light, medium exposure with blue, and high with red.

Since all three primary colors are introduced in the process, it is theoretically possible to produce the entire spectrum in the composite. Corresponding parts on the three radiographs will be at differing densities; consequently, the amount of light absorbed by each will vary. For example, Donovan's exposures were projected with red, green, and blue light on radiographs at high, medium, and low kilovoltages respectively. The more dense material, bone, appears predominantly red while the less dense material appears as a blend of these colors. (In this example, one must remember that positives, or reversals are used). A change in hue is noticeable at interfaces due to differing amounts of each color component being transmitted.

To simplify this process, Donovan used only two radiographs to make the composite. In this case, only the high and low kilovoltage transparencies were used. The results indicate that a more limited but acceptable portion of the color spectrum was still possible, while problems inherent in the process were greatly reduced.

In 1954, Blais and Schwerin[4] introduced a method that was a radically different approach to the problem. In their procedure, they introduced into the process phosphor intensifying screens. The film (standard commercial color) is sandwiched between two screens of different excitation color. The phosphors are chosen in such a manner that they respond differently to various x-ray wave lengths.

The exposure and development are then carried out in the usual fashion. The developed film will exhibit an extended range of color due to the various degrees of mixing. The amount of fluorescence given off by a phosphor is obviously a direct function of the quantity of x- or gamma radiation striking it. But it is also a fact that most phosphors are sensitive to harder or softer radiation depending on their nature. This means that the hue is a function of both quantity and quality of incidence radiation.

This technique was also used by Bryce[5] in 1955. In addition, Bryce also made some advancement in indirect color radiography. The first step involves making a positive plate by contact printing. These transparencies

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[4]J. M. Blais, M.D., and A. K. Schwerin, M.D., "A New Color-Radiographic Process," The Focal Spot, vol. 11 (1954), pp65-66.

[5]M. B. Bryce, "Experimental Color Radiography," British Journal of Radiology, vol. 28 (1955), pp 552-53.

are then printed onto color printing paper. These exposures are made through different filters. Like Donovan, Bryce was able to get good two-color printing with a degree of mixing to produce a limited spectrum.

In 1958, Beyer,[6] working for the Argonne National Laboratory, initiated a study of possible techniques for color radiography. His investigation had two distinct methods of approach; one being an indirect "flash" technique, and the other a more direct phosphor application.

Beyer's first technique is clearly indirect in nature. It entails taking the radiograph in the usual fashion using commercial color film in the place of conventional x-ray film. Also, calcium tungstate intensifying screens were applied in the conventional fashion. After exposure, the film is processed in a manner that will add the desired color contrast. This method involves placing the film in the first developer until partial development is obtained. At this time, the film is re-exposed by flashing with a colored light, either red or green. The regular techniques for color film development are then completed. At the conclusion of the development process, the film displays the desired hue contrast.

Beyer's second and more direct approach is the inclusion of phosphors in solutions used as dye penetrants. In this fashion, the phosphors are incorporated into the surface cracks of the specimen. The phosphors that Beyer used were those found in color television sets. These were

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[6]Norman S. Beyer, Color Radiography, Special Materials and Services Division, Argonne National Laboratory, Argonne, Illinois (October, 1961), pp203-217.

chosen because they possessed the desired physical properties and were readily available.

Opposite faces were treated with different solutions so that surface cracks on different faces were filled with phosphors of different colors. The color film is placed in contact with one of the "tagged" surfaces and the entire specimen-film assembly is placed in a light-free envelope. This entire procedure must be done in a dark environment.

The specimen is then radiographed using standard techniques. The colors originating from the phosphors are thus imprinted on the film. Using this method not only allows one to detect cracks by color change, but also gives an indication to their depth by observation of their color. In other words, the cracks on the bottom surface will appear as the color of the bottom phosphor and similarly for the top. Of course, interior cracks still appear as changes in density of the basic color of the radiograph. If commercial color film were used, a blue-green to blue base color would appear. This is simply a characteristic of the dyes being used in the manufacture of the film. In other words, if color film were exposed similarly to radiographic film and then developed as prescribed by the manufacturer, a predominantly blue hue would be present.

THEORY

Direct Color Radiography

Direct color radiography has been defined as a process in which color is added to the radiograph during exposure to x- or gamma radiation. Of necessity for this process is an agent to convert this extremely short wave length radiation to visible light. To be effective, this agent must possess special characteristics. It should have the ability to separate various energy levels in the x- or gamma range of the spectrum. The response to the separation should be the emission of visible light in varying hues. This process is actually one of transferring one portion of the spectrum, x- and gamma wave length, into another, visible wave length.

Two areas exist that could possible contain this agent. The first of these is the familiar phosphor. Phosphors function by absorbing energy and then glowing when a sufficient quantity of this energy has been absorbed. The light given off can then be recorded by standard color film. Another possible approach is the modification of the film dye to be sensitive in the x- or gamma range of wave length. The film can be manufactured containing several layers of these dyes sensitive to sub-intervals in the short wave length portion of the spectrum.

Phosphors can be utilized in two distinct ways. They can either be fabricated into screens or incorporated into the emulsion layers of the film. Problems inherent with the use of phosphors make the latter appear completely improbable. These problems are of such a nature to be of central importance in consideration of direct color radiography. There is a great range of energies, wave lengths, used in the production of radiographs. One specimen may require very low energy on an x-ray tube. Others require very high energy and corresponding short wave length. This consideration alone would make it impossible to achieve the production of "standard color radiographic film." In one case, the phosphors chosen properly with respect to excitation wave length would be totally useless when applied to the higher energy radiation.

One solution of this problem could be the indexing of phosphors as to their excitation wave length and radiating color. Upon studying the specimen to be radiographed, one could decide which combination of phosphors should be applied. Inherent in this process is the necessity to be able to interchange many possible combinations of phosphors. For this reason, the screens possess greater possibilities than the dyes. This results from the physical fact that it is easier to interchange screens than emulsion layers on a film.

The actual process of taking the color radiograph, assuming the above problems can be overcome, would follow a process such as the one that will now be outlined. The specimen must first be studied to make calculations concerning the choice of phosphors. These calculations are centered about the portion of interest of the specimen. Three esposures emphasizing different areas could be utilized. Calculations of the wave length necessary to penetrate these desired sections are then utilized in the choice of phosphor screens. This procedure can best be illustrated by the use of an example. Suppose the test specimen is the stepwedge shown in Figure 2-1,

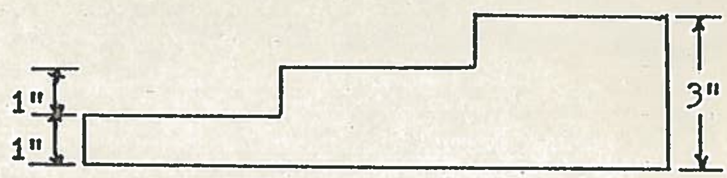


FIGURE 2-1

STEPWEDGE

Using the tables in Richardson's manual,[2] it is found that 150 Kev is necessary to penetrate the one inch section; 200 Kev for the two inch section; and 250 Kev for the three inch section. Now use a phosphor screen sensitive to 150 Kev that emits blue light, a green phosphor screen sensitive to 200 Kev, and a red phosphor sensitive to 250 Kev. These three phosphor screens are then encased with color film in a light-free packet. We are now ready to make the exposure. The actual exposing is done in three discrete steps. The first exposure is at 150 Kev. This is able to penetrate only the one inch section. It then excites the blue phosphor which in turn is recorded on the film. The next exposure, at 200 Kev, penetrates both the one and two inch sections. However, only the green phosphor is sensitive to this range energy. Consequently, the two inch section is now recorded as green and the one inch section is now a combination of blue and green on the film. During the third exposure, at 250 Kev, all three areas are penetrated. In a process similar to the one just described, the three inch section is now shown as red; the two inch section as red and green; and the one inch section as red, green, and blue. The color film is then removed and developed in the usual fashion. The developed film now exhibits hues that are results of the mixing described above.

Additional problems also exist in obtaining color radiographs in a process similar to the one outlined in this discussion. The calculations of exposure time for the three settings are significantly more complex than in usual radiographic procedures when only one exposure is utilized.

Indirect Color Radiography

As previously stated, color radiographs can be produced through photographic manipulations. These processes may seem varied, but actually all are only slight deviations from the basic indirect radiography process. This process will now be presented, and an attempt will be made to show how variations of this process have been used to produce color radiographs.

By taking advantage of the properties of color film and the color mixing processes, a color reproduction of a black and white film can be made. These results can be obtained by projecting different parts of the black and white film onto the different emulsion layers of the color film. Many processes have been devised to achieve this result. The most obvious method is to take multiple exposures emphasizing different parts of the specimen, and to project them individually onto the different emulsion layers. This can be accomplished through the use of different color lights for projection. Donovan[3] actually used this method to produce color radiographs.

The "flash" method presented by Beyer[6] at first glance seems quite different from other methods of indirect color radiography. Actually the only difference lies in what is used as the original radiograph from which the projections are made. The top, or blue sensitive, layer of tripack film can be used singularly as radiographic film. If color film were used in radiography and only the blue layer developed, a radiograph would be obtained differing only from the conventional in the hue of the final picture. In this case, shades of blue would replace the usual grey shadings. By exposing color film to x- or gamma rays through radiography and developing only the top, blue emulsion layer, we have, in effect, produced a self-contained image to be further imposed on the film. This is done simply by flashing with a colored light.

Another variation of the indirect method would be to obtain in a different manner the radiographs that emphasize the selected parts of the specimen. An example would be a contact print reversal technique. In this process, an exact opposite of the radiograph would be obtained. It would then be possible to obtain a composite by projecting the two radiographs with different color lights as in Donovan's method previously discussed. This method is actually the one used to produce the color radiographs in this thesis, and will be discussed in detail in the next section.

In summary, light areas on a radiograph when projected by a colored light onto color film will appear as that color on the film. Dark areas on the radiograph will absorb the light and not be projected. If a radiograph displaying the same areas by shadings contrasting with the original is projected with a different color light onto the same film, entirely different areas will be projected. If reversals are used, dark areas become light areas and are now projected. Shades lying between the two extremes will be projected, to a limited extent, by each exposure and appear as an area of color mixing. The mixed color may be a different or new color if primary colors are used.

PROCEDURE

The process by which the color radiographs included in this thesis were produced will now be presented. This method is indirect by nature and a new combination of some methods previously presented.

A "black and white" radiograph is obtained in the usual fashion. The image produced in this process can be thought of as a photographic negative. This terminology is derived from the fact that less dense sections appear as darker shades on a radiograph in an analogous fashion to white objects appearing dark on a photographic negative.

The first step in the ultimate achievement of a color radiograph is the simple reversal of this negative to obtain a positive. This is done through a contact printing process. This consists of placing a film in contact with the negative and exposing it to light. The light is absorbed in the negative in proportion to the amount of silver deposited during the original exposure and development. The amount remaining for exposure of the second film is, therefore, an inverse function of the original exposure. The end result is an image displaying less dense areas of the original specimen as light areas on the final radiograph. Since the two films are in direct contact during the exposure to light, a minimum distortion of image is achieved. (An alternate method to achieve this reversal is presented as an appendix to this thesis).

We now have two radiographs of the specimen, a negative and a positive. These two possess the necessary property; the contrast between similar points on the two is a maximum. In other words, a completely transparent area of one corresponds to the area of maximum opaqueness on the other.

As in the case of all indirect color radiography, color is added by exposing the two radiographs to different color lights. The physical setup is illustrated in Figure 3-1. The camera contains a standard tri-pack color film. The film is the ultimate device upon which color will be viewed. The basic colors of red, green, and blue can be obtained in either of two ways: use of colored light behind the negative and positive, or white light passing through color filters on the camera. If color bulbs are used, they combine to form different colors in the color additive process shown in Figure 1-4. Color filters absorb certain wave lengths and emit only those remaining through the color subtraction process shown in Figure 1-5. By combining these two, a color bulb and a filter of a different color, we are able to obtain almost any color desired. An example of a color radiograph using colored bulbs is Figure 4-7, and one using color filters is Figure 4-8.

The first step is to expose the film to a color through either the positive or negative radiograph. This amounts to taking a picture of the radiograph illuminated by the color bulb. The radiograph is then replaced by its reversal making sure alignment is maintained. In order to facilitate this change, a holding and positioning device for the radiographs was designed. It is shown in Figure 3-2.

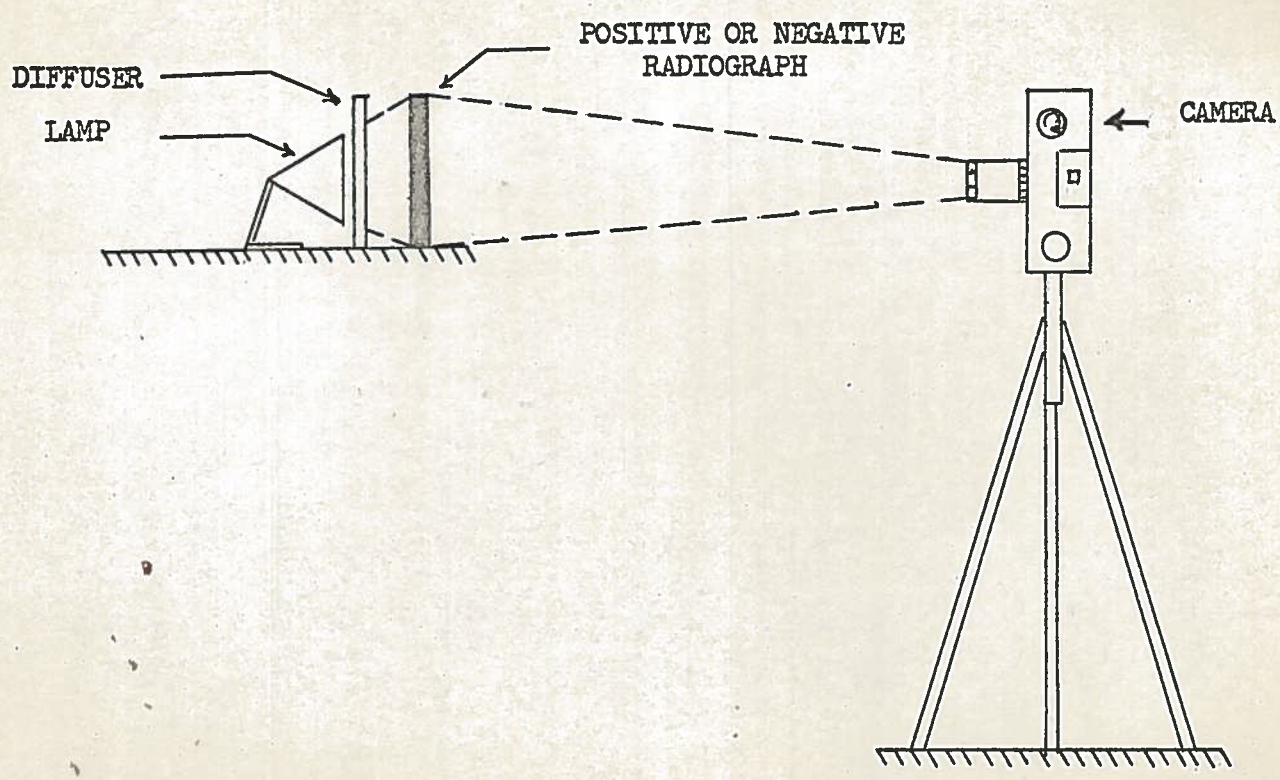


FIGURE 3-1

ARRANGEMENT FOR INDIRECT COLOR RADIOGRAPHY

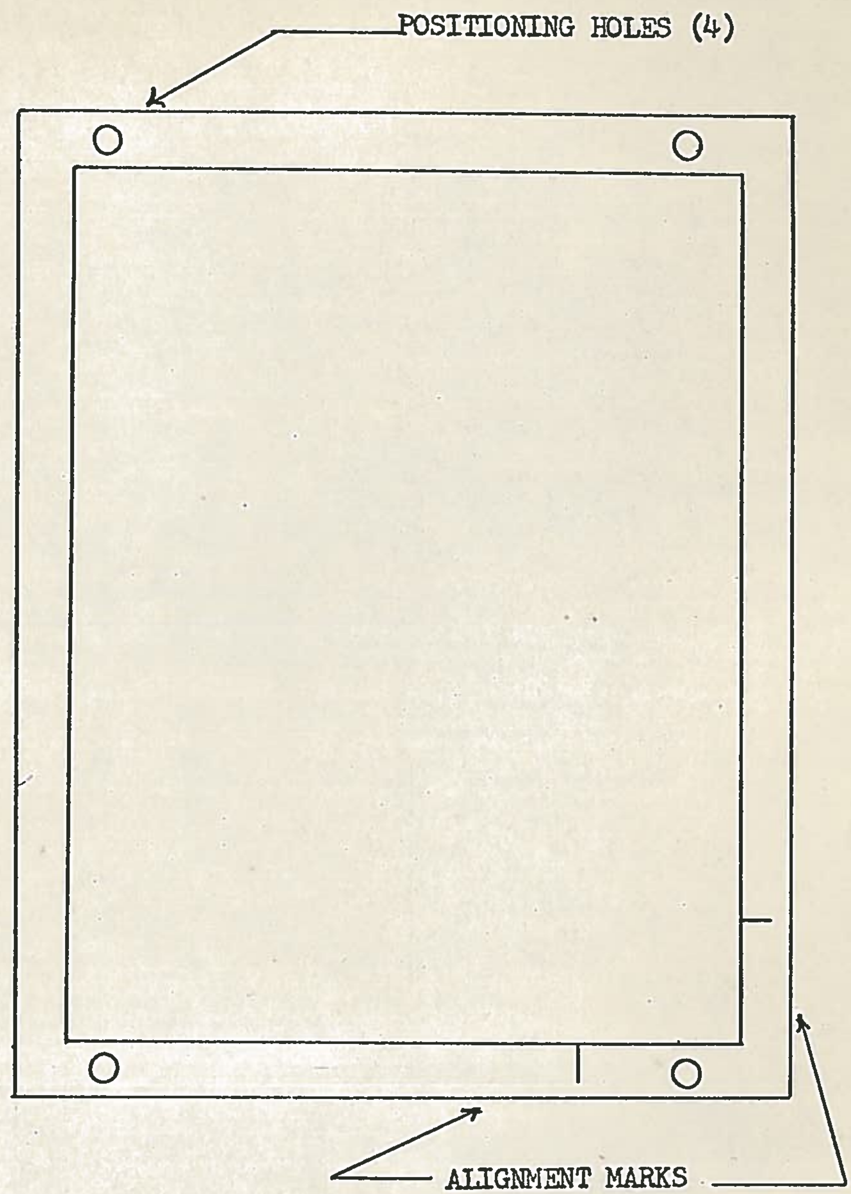


FIGURE 3-2

RADIOGRAPH HOLDER

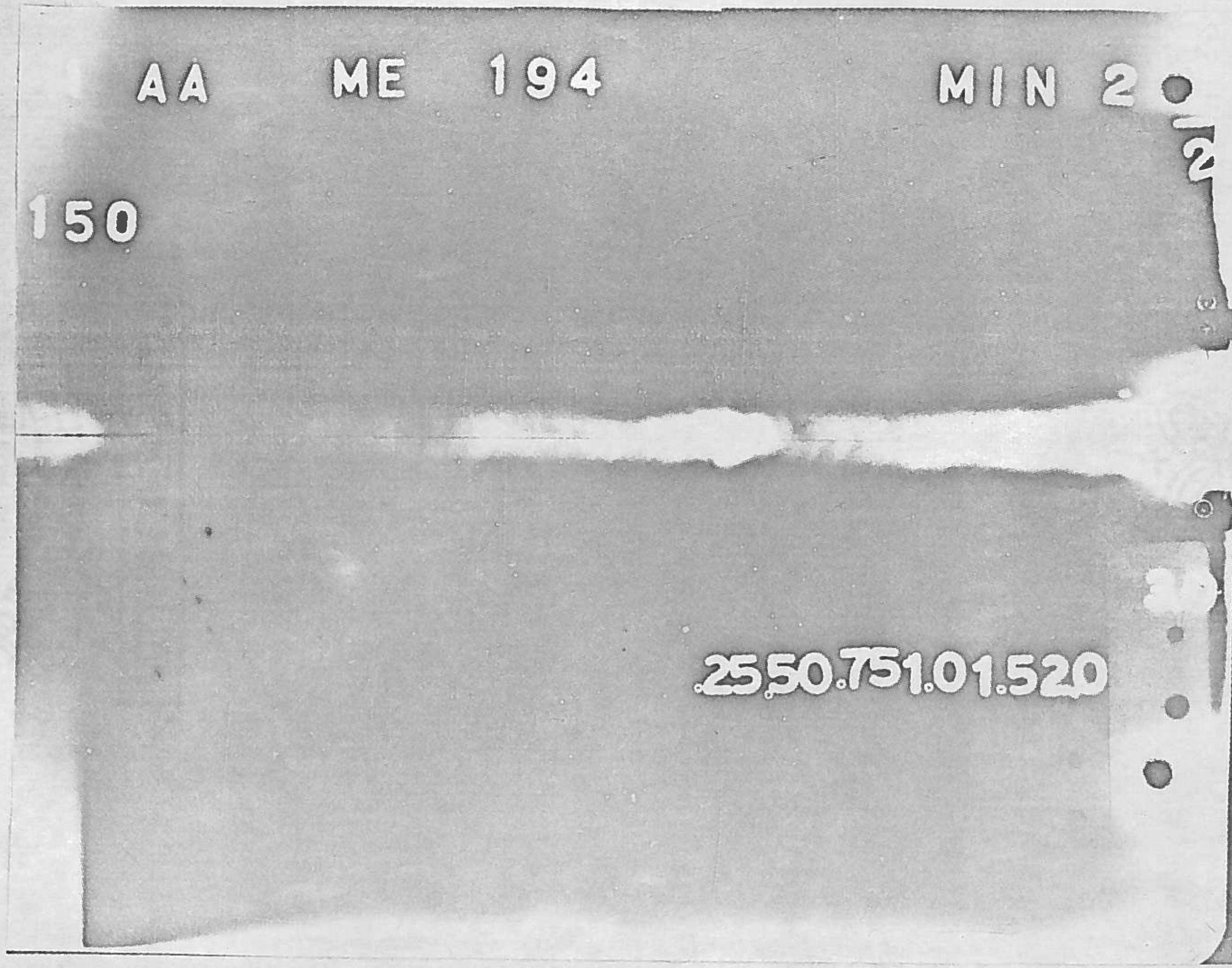
The two transparencies are first placed in contact, with the proper alignment, and put on the frame. Four holes are punched to secure the radiographs to the frame. To insure proper alignment; two reference marks are drawn on each radiograph corresponding to marks on the frame. The radiographs are then positioned by bolting them to the frame making sure the marks correspond.

Once the reversal is in place, we simply expose it with a different color light. In effect, we have activated different emulsion layers of the film. Consequently, the film will show the different areas of the specimen as color contrast. Through this process, we have achieved our goal; the production of a radiograph which displays differences in density and thickness as a change in hue.

An interesting result occurs when alignment is not exact during the changing of negative and positive. If the error is slight, corresponding parts will be transposed slightly on the composite. This has the effect of giving the radiograph a three dimensional appearance. Here we are getting into the area of stereoradiography. An example of this can be seen in Figure 4-6.

RESULTS

Examples of color radiographs produced by the process outlined in this thesis are included on the following pages. These results were first recorded on slides and then transferred to prints in commercial facilities. For sake of comparison, black and white prints of the original radiographs are included in some cases.


AA ME 194 MIN 2
150
.25 .50 .75 1.0 1.5 2.0

LM AA ME 194 MIN 2 1/2

150

3.0

.25 .50 .75 1.0 1.5 2.0

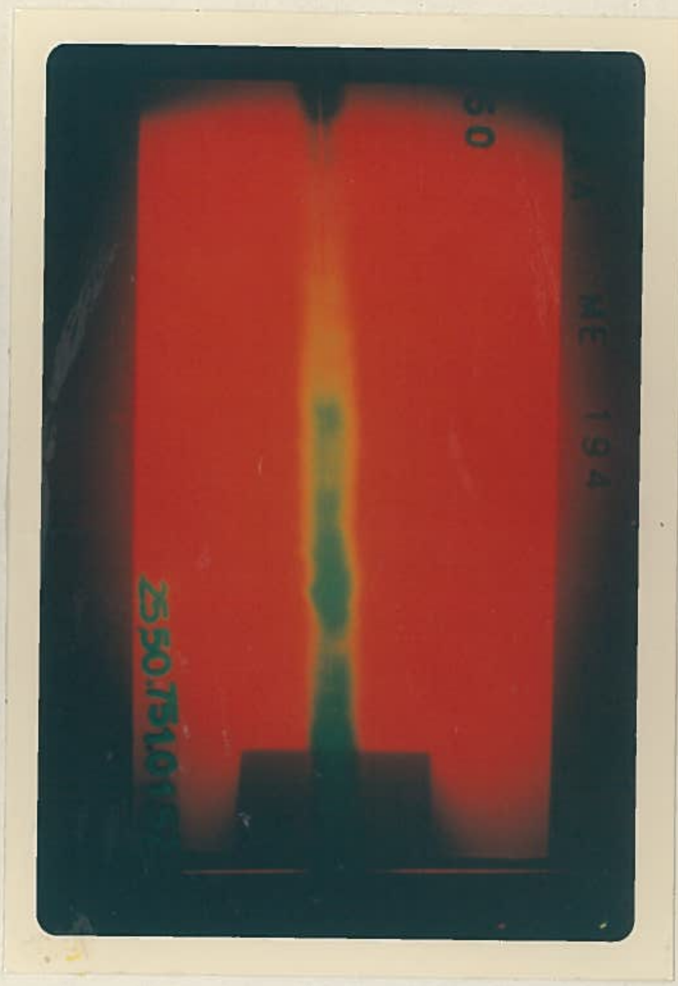
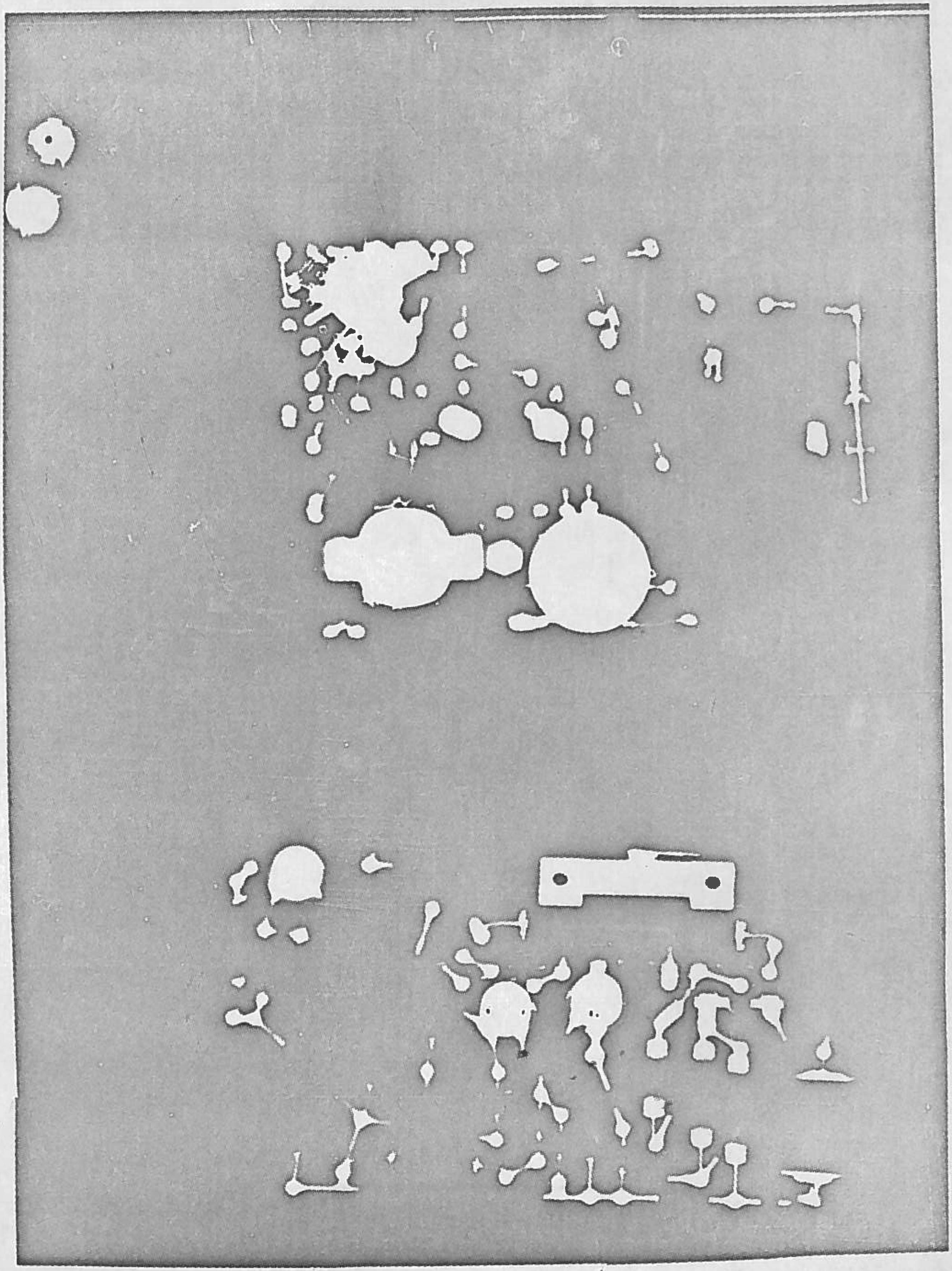


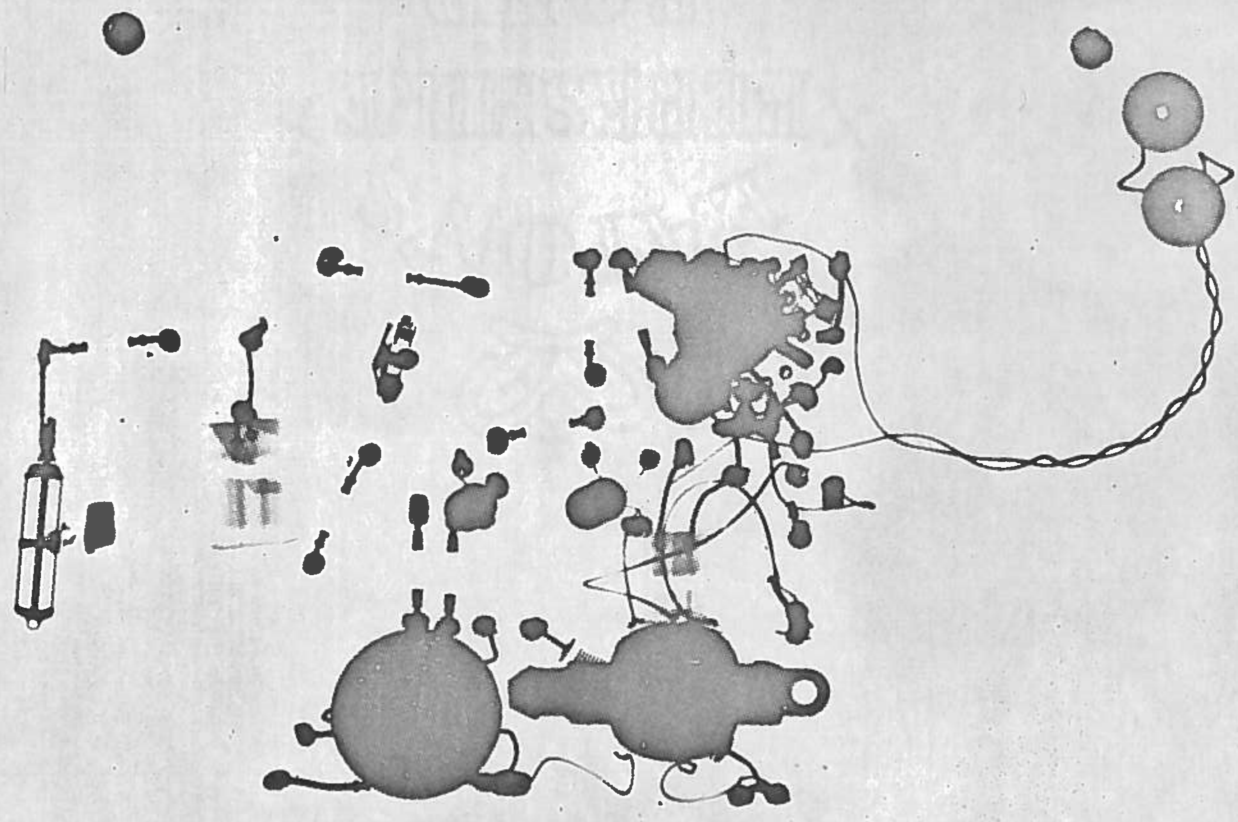
FIGURE 4-3

COLOR REPRODUCTION OF FIGURE 4-1

White light - Red filter - Positive

White light - Green filter - Negative





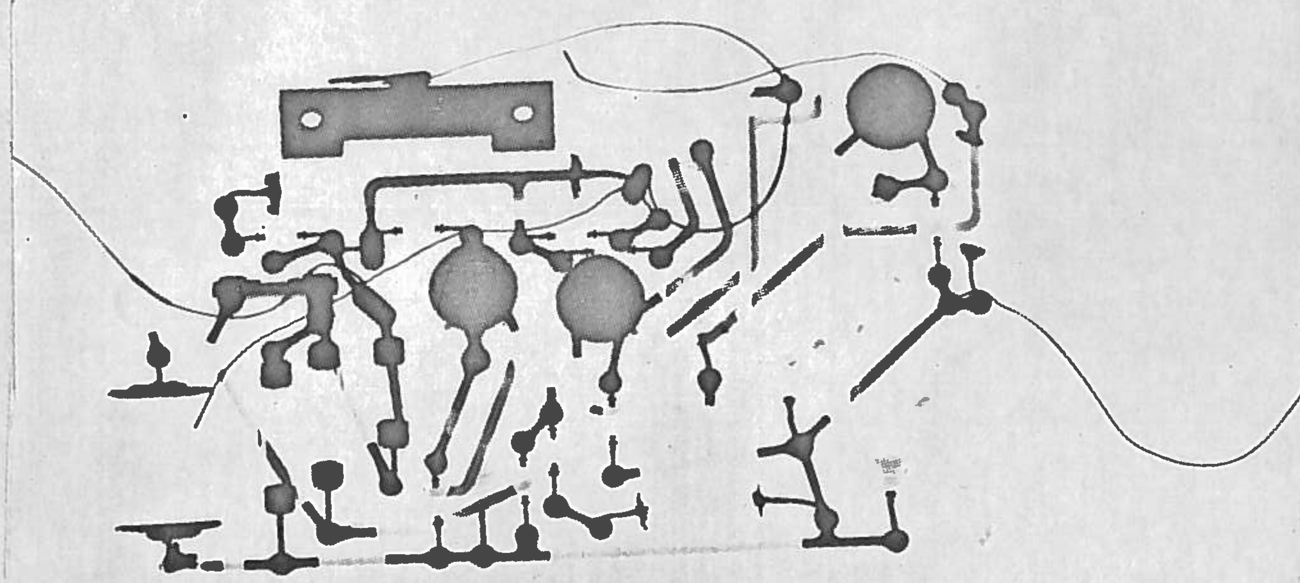


FIGURE 4-6

COLOR REPRODUCTION OF FIGURE 4-4

White light - Red filter - Positive

White light - Green filter - Negative

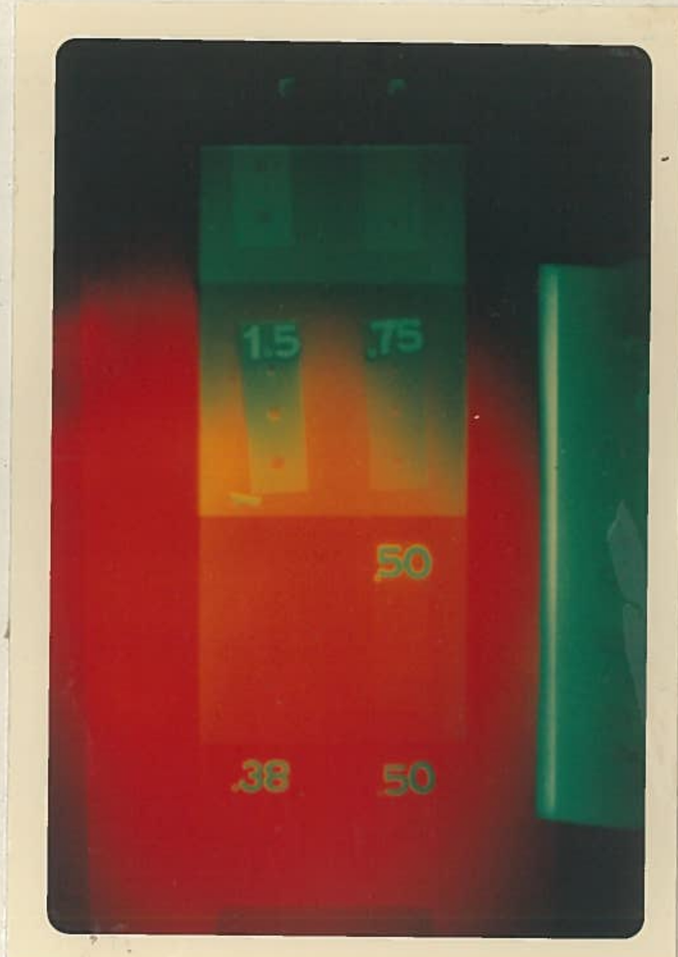


FIGURE 4-7

Red blub - No filter - Positive

Green bulb - No filter - Negative

FIGURE 4-8

Red light - Green filter - Positive

Blue light - No filter - Negative

FIGURE 4-9

White light - Red filter - Positive

Blue light - Green filter - Negative

FIGURE 4-10

Red light - Green filter - Positive

White light - Red filter - Negative

FIGURE 4-11
White light - Green filter - Positive

White light - Red filter - Negative

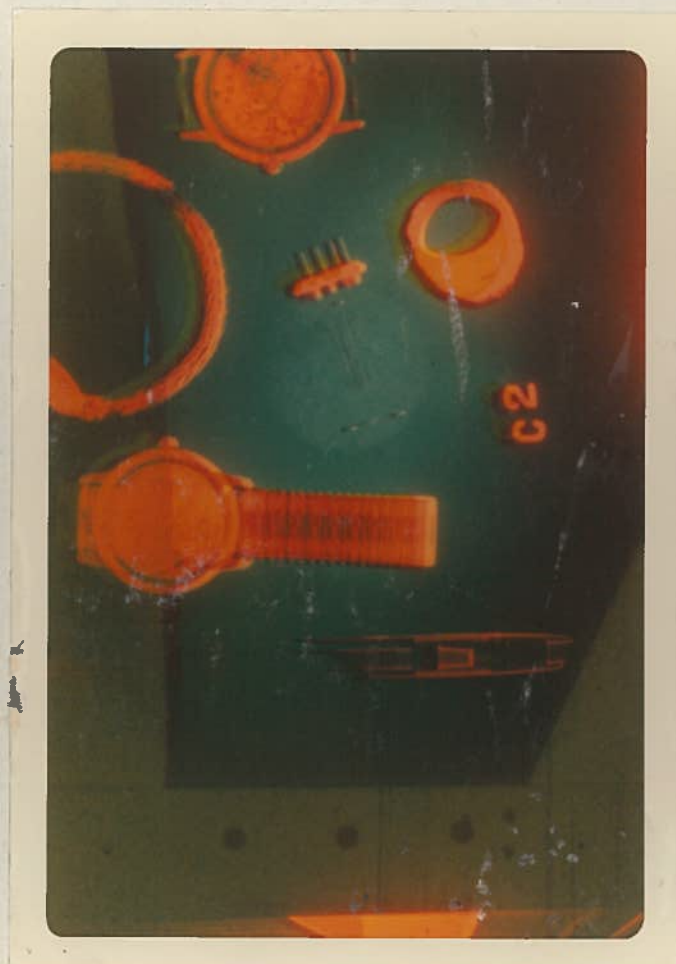


FIGURE 4-12

White light - Green filter - Positive

White light - Red filter - Negative

CONCLUSIONS AND RECOMMENDATIONS

After a thorough investigation of the work that has been done, I find that color radiography's future is very uncertain. The results which have been obtained are comparable but not better than results which could have been obtained using conventional black and white methods. Admittedly, color radiographs are more pleasant to view; but their costs of production makes them undesirable from an economic point of view.

Indirect color radiography has reached a point to where color radiographs can be obtained through a series of photographic manipulations. This thesis has presented for the first time a method of producing color radiographs using only commercial photographic equipment. No elaborate equipment was devised or used. In fact, the results were obtained on 35 mm. slides and the development carried out by using available commercial facilities.

Direct color radiography must wait for the development of phosphors, whose characteristics have been outlined in this thesis, before any significant progress can be made. It is therefore recommended that any further work in this field be directed toward the development of the phosphors necessary to carry out direct color radiography.

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APPENDIX I

Direct Reversal

1. First Developer (3-4 times normal strength)

Methol	35 grains	2 grams
Sodium sulphite, anhydrous	3½ ozs.	90 grams
Hydroquinone	140 grains	8 grams
Sodium carbonate, anhydrous	2 ozs.	50 grams
Potassiun thiocyanate	35 grains	2 grams
Water to make	40 ozs.	1000 cc

2. Wash

3. Bleach (leave until negative disappears)

Potassium bichromate	88 grains	5 grams
Sulphuric acid, concentrated	96 minims	5 cc
Water to make	40 ozs.	1000 cc

4. Cleansing bath (3-4 minutes)

Sodium sulphite, anhydrous	1 ozs.	25 grams
Sodium hydroxide, 10%	96 minims	5 cc
Water to make	40 ozs.	1000 cc

5. Wash

6. Expose to 100 Watt bulb at 12 in. for 5-7 minutes

7. Develop

APPENDIX II

DATA

October 15, 1955
Kodak Kodachrome
taken at 4'
Light Bulbs - Red 25W
Blue 25W
Green 25W

Slide No.	Color Bulb	Pos. or Neg.	Time
1	red	neg.	30 sec
2	red	neg.	30
	green	pos.	20
3	green	pos.	20
4	green	pos.	20
	blue	neg.	30
5	blue	neg.	30
6	blue	neg.	30
	red	pos.	20
7	red	pos.	20
8	red	pos.	20
	green	neg.	30
9	green	neg.	30
10	green	neg.	30
	blue	pos.	20
11	blue	pos.	20
12	blue	pos.	20
	red	neg.	30

Slide No.	Color Bulb	Pos. or Neg.	Time
13	red	neg.	60 sec
14	red	neg.	90
15	red	neg.	30
	blue	neg.	30
16	red	neg.	30
	green	neg.	30
17	green	neg.	30
	blue	neg.	30
18	blue	neg.	30
	green	neg.	30
	red	neg.	30
19	red	pos.	45
20	red	pos.	10
21	red	pos.	10
	blue	pos.	10
	green	pos.	10

February 16, 1966
Slides - Kodak Ektachrome
taken at 20"

Slide No.	Filter	Color Bulb	Pos. or Neg.	Time
1	red	white	neg.	5 sec.
2	red	white	neg.	10
3	green	white	neg.	5
4	green	white	neg.	10
5	green	red	neg.	20
6	green	red	neg.	20
	red	white	pos.	20
7	red	green	pos.	flash
8	red	green	pos.	5
	none	red	neg.	15
9	void			
10	green	red	neg.	20
	red	green	neg.	20
11	red	blue	neg.	20
12	green	blue	neg.	20
13	green	blue	neg.	20
	red	blue	neg.	20
14	red	blue	neg.	15
	red	blue	neg.	15
	none	blue	neg.	15
15	same as 14 with pos. and exposure = 7 sec. each			
16	same as 15 with pos. and exposure = 15 sec. each			

Slide No.	Filter	Color Bulb	Pos. or Neg.	Time
17	none	blue	pos.	10 sec
	green	blue	pos.	10
	red	blue	neg.	20
18	none	blue	pos.	10
	green	blue	neg.	20
	red	blue	neg.	20
19	none	blue	neg.	20
	green	blue	neg.	20
	red	blue	pos.	10
20	none	blue	neg.	20
	green	blue	pos.	10
	red	blue	pos.	10

February 18, 1966
Film - Wards'
taken at 14 in.

Slide No.	Bulb	Filter	Pos. or Neg.	Time
1	white	red	neg.	flash
	white	green	pos.	flasn
2	blue	red	pos.	flash
3	blue	green	neg.	20 sec
	white	red	pos.	2
4	blue	none	pos.	2
	blue	green	neg.	20
6	white	red	pos.	flash
	white	red	pos.	flash
7	blue	none	pos.	8
	blue	red	neg.	15
	white	red	neg.	2
8	void			
9	blue	none	neg.	20
	blue	red	neg.	20
	white	red	pos.	flash
10	void			
11	blue	none	neg.	20
	white	red	pos.	flash
12	blue	none	neg.	25
	white	red	pos.	flash

Slide No.	Bulb	Filter	Pos. or Neg.	Time
13	white	green	neg.	2 sec
	blue	red	pos.	10
14	blue	none	neg.	20
	white	red	pos.	flash
15	white	green	neg.	2
	blue	red	pos.	10
16	white	red	pos.	flash
	blue	none	neg.	20
17	white	red	pos.	flash
	blue	green	neg.	20
18	white	red	pos.	flash
	blue	green	neg.	20
19	white	red	pos.	flash
	blue	none	neg.	20
20	white	red	pos.	flash
	blue	none	neg.	20
	white	green	neg.	20
21	white	red	neg.	2
	white	green	pos.	flash

March 5, 1966
Film - Kodak Kodachrome
taken at 14 ins.

Slide No.	Bulb	Filter	Pos. or Neg.	Time
1	white	red	pos.	flash
	blue	none	neg.	20 sec
2	blue	none	neg.	40
	white	red	pos.	flash
3	white	red	neg.	2
	blue	none	pos.	10
4	white	red	neg.	2
	blue	none	pos.	20
5	white	red	pos.	flash
	white	green	neg.	2
6	white	green	pos.	flash
	white	red	neg.	20
7	white	red	pos.	flash
	blue	green	neg.	20
8	white	red	pos.	flash
	red	green	neg.	20
9	red	green	pos.	10
	white	red	neg.	2
10	white	green	pos.	flash
	white	green	neg.	2
	blue	none	neg.	20

Slide No.	Bulb	Filter	Pos. or Neg.	Time
11	blue	none	neg.	20 sec
	white	red	pos.	flash
	white	green	pos.	flash
12	white	red	neg.	2
	white	green	pos.	flash
	white	red	pos.	flash
13	white	red	pos.	flash
	white	green	neg.	2
	white	red	neg.	2
14	blue	red	pos.	10
	red	green	neg.	20
15	white	red	neg.	2
	red	green	neg.	20
16	red	green	pos.	10
	white	green	neg.	2
17	void			
18	red	green	neg.	20
	white	green	pos.	flash
19	green	red	neg.	20
	white	green	pos.	flash
20	green	red	pos.	5
	white	green	neg.	2

April 5, 1966
Film - Kodak Kodachrome
taken at 14 ins.

Slide No.	Bulb	Filter	Pos. or Neg.	Time
1	white	red	pos.	flash
	red	green	neg.	15 sec
2	white	green	neg.	2
	white	red	pos.	flash
3	blue	none	neg.	20
	red	green	pos.	2
4	blue	none	neg.	20
	white	red	pos.	flash
5	white	green	pos.	flash
	white	red	neg.	2
6	white	green	neg.	2
	red	green	pos.	5
7	white	red	pos.	flash
	white	green	neg.	2
8	white	green	pos.	flash
	white	red	neg.	2
9	white	red	pos.	flash
	red	green	neg.	15
10	white	red	pos.	flash
	green	red	neg.	15

Slide No.	Bulb	Filter	Pos. or Neg.	Time
11	white	red	pos.	flash
	blue	green	neg.	20 sec
12	white	red	pos.	flash
	blue	none	neg.	20
13	red	green	pos.	5
	white	green	neg.	2
14	blue	none	pos.	5
	white	red	neg.	2
15	blue	green	pos.	5
	white	red	neg.	2
16	white	red	neg.	2
	white	green	pos.	flash
17	white	red	pos.	flash
	blue	none	neg.	20
18	void			
19	red	green	pos.	5
	white	red	neg.	2
20	void			

April 19, 1966
Film - Kodak Kodachrome
taken at 14 ins.

Slide No.	Bulb	Filter	Pos. or Neg.	Time
1	void			
2	white	red	pos.	flash
	blue	none	neg.	15 sec
3	blue	none	neg.	10
	red	none	pos.	10
4	white	red	pos.	flash
	white	green	neg.	5
5	white	red	neg.	2
	white	green	pos.	flash
8	void			
9	white	red	pos.	flash
	blue	none	neg.	10
10	white	red	pos.	flash
	blue	none	neg.	10
11	white	red	pos.	flash
	white	green	neg.	5
12	void			
13	white	red	pos.	flash
	green	none	neg.	10
14	red	none	pos.	5
	blue	red	neg.	10

Slide No.	Bulb	Filter	Pos. or Neg.	Time
15	blue	none	pos.	5 sec
	red	none	neg.	5
16	blue	green	pos.	5
	white	red	neg.	2
17	white	green	pos.	flash
	white	red	neg.	2
18	white	green	pos.	flash
	red	green	neg.	10
19	white	green	pos.	flash
	red	green	neg.	2
20	void			

VITA

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