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Color Compensating Filters with Infrared Film

The use of color compensating filters in the CC20 range resulted in density increases in Kodak Aerochrome infrared film, type 2443.

Abstract: *Filters which remove the visual spectral components (minus visual) produce optical density increases in all three layers of Kodak Aerochrome infrared film, type 2443. The increased density was reflected in a shift of the characteristic curves of the film; the amount of shift was dependent upon the filtration used. In this study, color compensating filters (CC filters) in the CC20 range were used. Two types of density increases were observed. The first resulted in the attenuation of reflected energy in certain spectral regions caused by the filters used and the amount of attenuation was measured as a density increase relative to a standard exposure of the same subject; the standard being Type 2443 exposed through a Wratten 12 (W12) filter. The second type of density increase, called an attenuation factor, was detected and resulted from attenuation of the other dye layers present in the film. The attenuation factor was independent of the photographic CC filter factor.*

Statistical analysis of density values measured on operational test film showed that the density increases were measurable and normally large enough to cause the characteristic curves to shift in the direction of increased density (i.e., towards the red characteristic curve). The distributions represented by the blue, green, and red characteristic curves shifted to the right with the blue and green distributions shifting by an amount that would place them within the red distribution if a larger value minus auxiliary filter were used.

Introduction

A CF100 "Canuck" aircraft was used to conduct a series of flights at altitudes of 20,000 feet and 40,000 feet to carry out film/filter tests of Kodak Aerochrome infrared film, type 2443. The purpose was to determine the effect which color compensating filters have on type 2443 at flying altitudes that would be used by the Canada Centre for Remote Sensing (CCRS). It is reported by Worsfold (1972) and confirmed in field tests (Tarnocai and Thie, 1974) that the filter combination of W12+CC20M (W = Wratten, CC = Color Compensating) provides the best photographs in terms of image sharpness while retaining infrared data but the combination of W12+CC20B provides the best information in terms of infrared content.

The CC20 series of color compensating filters were used for the tests discussed in this paper. The original analysis (Worsfold, 1972) was a qualitative assessment of a series of selected seventy millimetre stereotriplet transparencies. This paper is concerned with a more quantitative approach to the same analysis. The middle frame of the original stereotriplets were used for a series of random densitometer measurements. The resulting data was subjected to statistical analysis. The results were compared with measurements made on a test standard 2443 film that was exposed using the recommended W12 filter. A series of sensitometric tests were carried out to confirm the theory.

In this paper, W12 refers to the standard film used. Test films are referred to as samples or as CC20___.

The various targets flown consisted of forested land, geologic formations, land forms, agricultural land, and industrial complexes. Three flight lines were flown near Kingston, Ontario, Canada (Worsfold, 1972). Two stereotriplets were selected from each flight line at each altitude.

The CF100 is a two-seat jet aircraft with cameras located in unpressurized areas but controlled from the navigator's section of the cockpit. To ensure that accurate flight lines were flown a closed-circuit television system (Worsfold, 1973 and Worsfold *et al.*, 1975) was installed in the gunbay. The unit was inclined fifteen degrees forward of vertical and its video monitor was installed in the cockpit.

The aircraft was fitted with seven Vinten aerial reconnaisance cameras; four Vinten 547's and three Vinten 492's. The focal length of each lens was three inches and a seventy millimetre format was used. Four cameras were located in the gunbay and three in the nose section. Two separate intervalometers controlled the two-camera arrays. Because they were not electrically synchronized, a slight difference in the imagery occurred between the two camera packages; however, this difference was not greater than the intervalometer timing of any one of the two camera systems.

Film/Filter Theory

The test film, Kodak type 2443, is sensitive to the visible spectrum from 400 nanometres to 700 nenometres and to the near infrared spectrum from 700 nanometres to 900 nanometres (Kodak Data for Aerial Photography M-29, 1971). The film has three dye layers: yellow, magenta, and cyan. The yellow layer controls production of the blue color; the magenta, the green; and the cyan, the red. The three layers of the film will be referred to here as the blue, green, and red layers respectively.

The blue layer registers the amount of green radiation to which the film has been exposed; the green layer, the amount of red radiation; and the red layer, the amount of near infrared radiation (Fritz, 1967). The relative density of the film is dependent upon the combined amount of green, red, and near infrared radiation received from the subject. A Wratten 12 (W12) filter is normally used with type 2443 to prevent wavelengths of less than 500 nanometres from sensitizing the film. The blue layer is sensitive to the 500—610 nanometre range; the green layer, the 500—690 nanometre range; and the red layer to the 500—900 nanometre range. The red layer is the least sensitive and hence is denser in the final product, accounting for the deep reddish color characteristic of type 2443 film.

The density of the red layer cannot be altered by an exposure change, as such a change would be the same for all three layers. To adjust for the density difference between the red layer and the other two layers, minus visual auxiliary filters should be used. These filters lower the sensitivity of the blue and green layers, thus increasing their density to a level that approaches that of the red layer (Pease and Bowden, 1969).

The color compensating series of filters are useful in reducing sensitivities. While they cause a moderate color change, in many cases this improves the final image. The filters cause an apparent enhancement of the red layer by increasing the density of the blue and/or green layers, thereby decreasing the density differences between the red layer and one or both of the other. The CC20 level was used since it falls approximately at the mid-point of the transmittance range for the total series CC05 to CC50. The CC20 filters affect exposure by approximately one third of an *f*-stop and the exposure with respect to the standard was so adjusted. Each CC20 filter reduces transmittances in one or two regions of its spectral range (Table 1, Figures 1, 2, 3, 4, 5, and 6).

The diffuse density (Figures 1, 2, 3, 4, 5, and 6) is the logarithm of the reciprocal of transmittance. The greater the diffuse den-

Table 1. Theoretical Effects of Colour Compensating Filters on Type 2443 Film

CC Filter	Absorption Region	Film Layers Affected
CC20B	Green and Red Radiation	Blue and Green
CC20G	Blue and Red Radiation	Green
CC20R	Blue and Green Radiation	Blue
CC20C	Red Radiation	Green
CC20M	Green Radiation	Blue
CC20Y	Blue Radiation	—

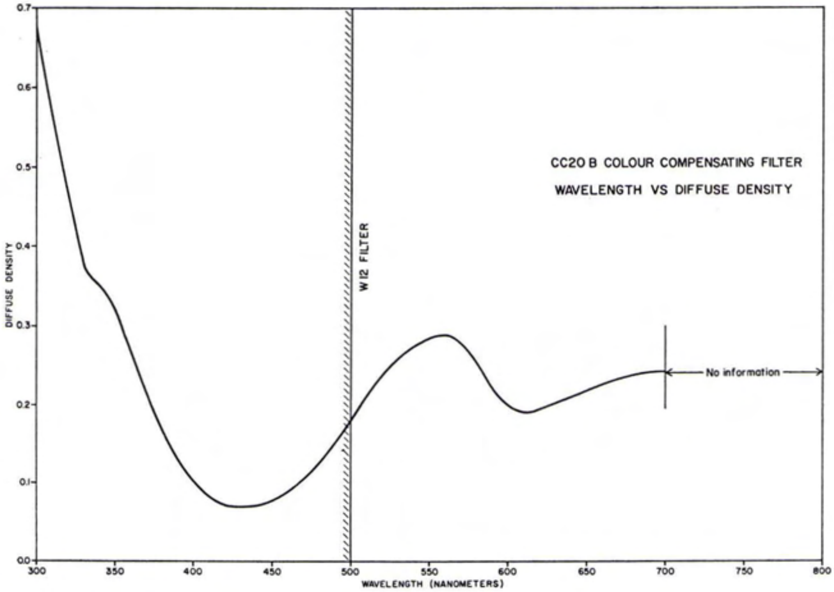


FIG. 1. Diffuse density curve for CC20B filter.

sity, the greater the absorption of the radiation in that spectral region. The CC filters are designed to accurately define the spectral region they affect. The curves are constructed from data contained in Kodak Technical Publication B-3 (1971).

PROCEDURES

One roll of type 2443 was exposed in the CCRS sensitometer. A twenty-one division step-wedge was used and the film was exposed through the various filter combinations. The resulting sensitometric curves were plotted for each filter combination (Fgiures 7, 8, 9, 10, 11, 12, and 13) and each combination was compared to the Kodak theoretical curve (Figure 14). The plotted curves are not averaged to smooth out the

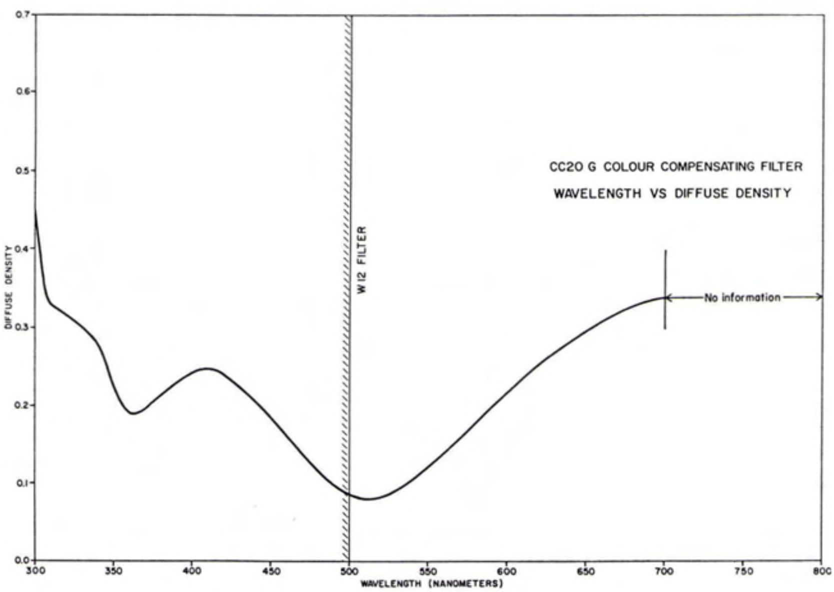


FIG. 2. Diffuse density curve for CC20G filter.

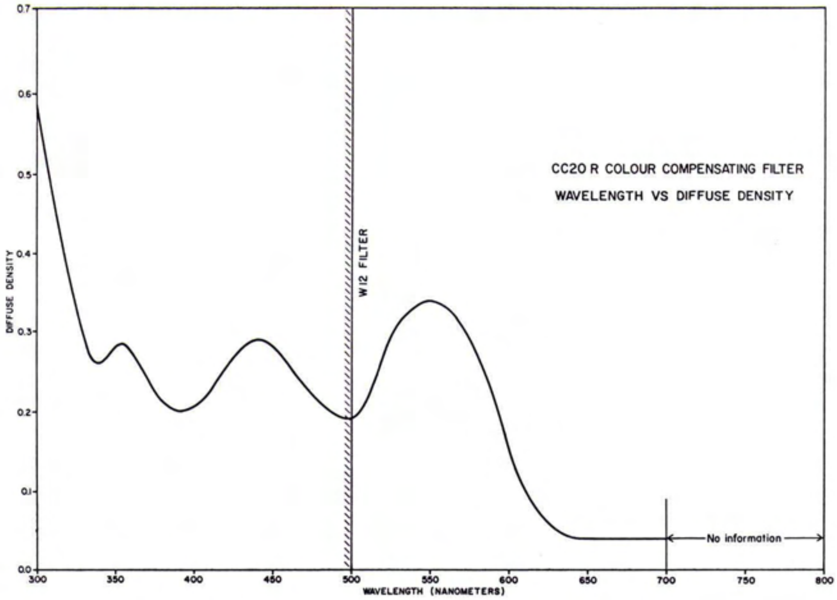


FIG. 3. Diffuse density curve for CC20R filter.

sensitometer values. By using a single roll of film, the processing was controlled, thus ensuring the constancy of the plotted curves. When reversal film such as type 2443 is used for sensitometric tests, a direct measurement of base plus fog density is impossible because the film cannot be cleared. To obtain a base plus fog approximation it was assumed that the first division of the step-wedge closely approached the base plus fog situation because it was the clearest portion of the test film. The neutral density reading is assumed to be the equivalent of a grayscale reading for color film since each layer contributes to the overall balance which the color of the gray step-wedge represents

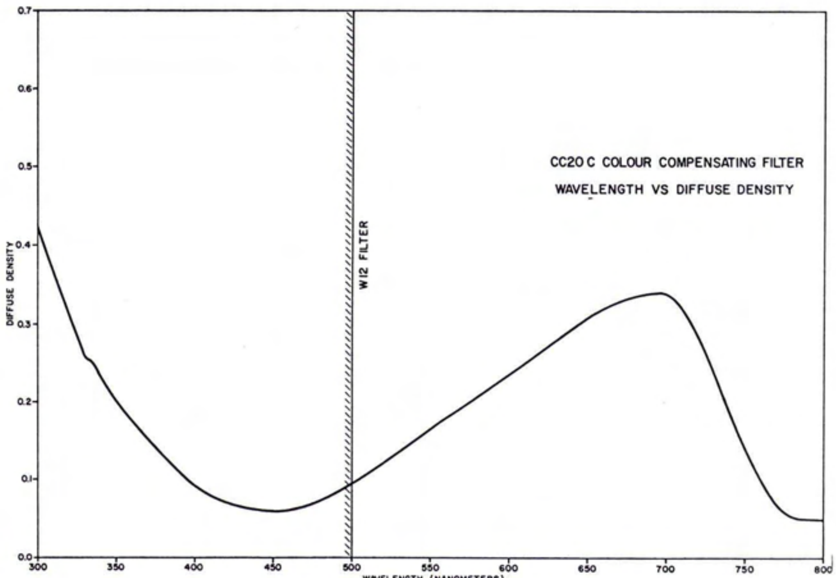


FIG. 4. Diffuse density curve for CC20C filter.

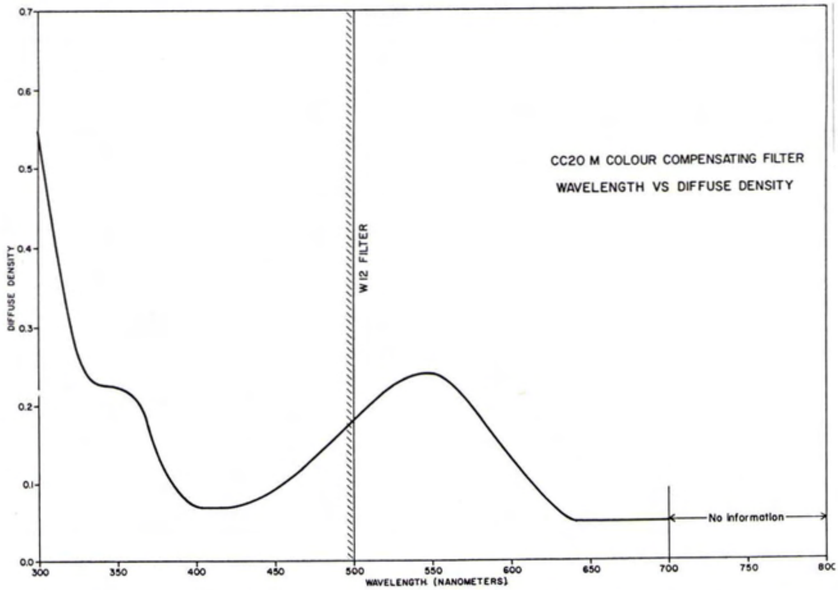


FIG. 5. Diffuse density curve for CC20M filter.

(James and Higgins, 1960). Whereas the neutral density reading of the first division was assumed to be the approximate base plug fog value, it must be noted that this does not account for the density level of the wedge. The base plus fog value is displayed to show that its correction to the density readings was negligible in that area of the sensitometric curve which causes density changes on the film. The MacBeth Quantalog Color Densitometer was used to analyze the step-wedges.

The W12 standard was used as a zero reference for the other test combinations. The difference between the density values for each layer of each filter combination and the

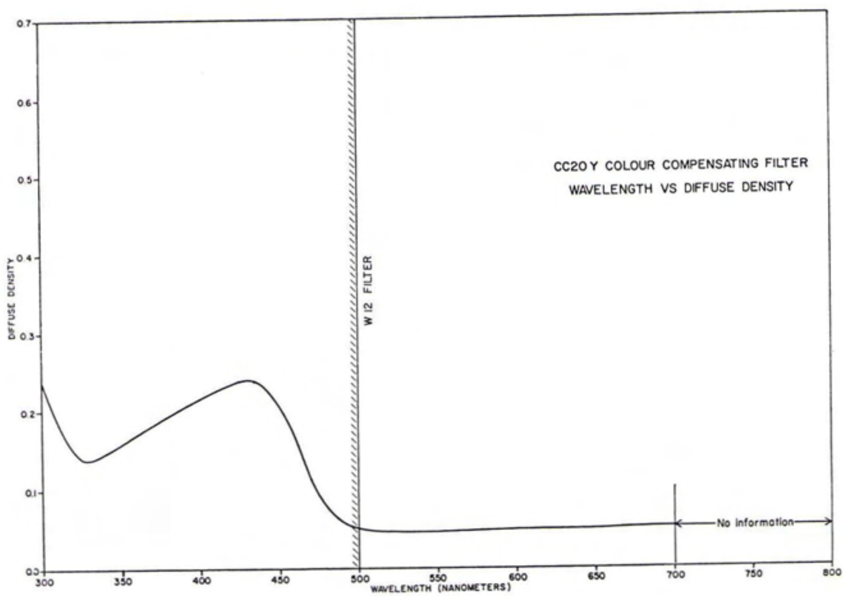


FIG. 6. Diffuse density curve for CC20Y filter.

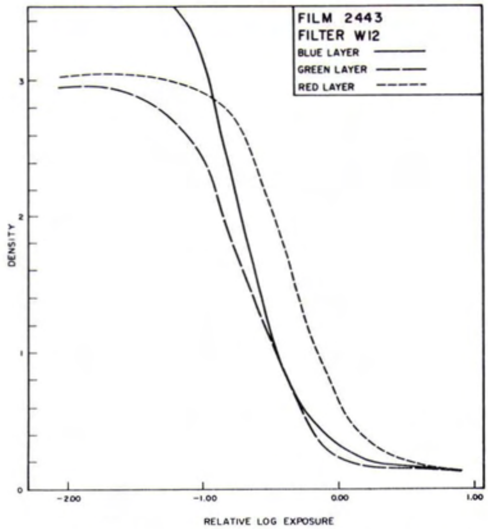


FIG. 7. Sensitometric curve for W12 test standard.

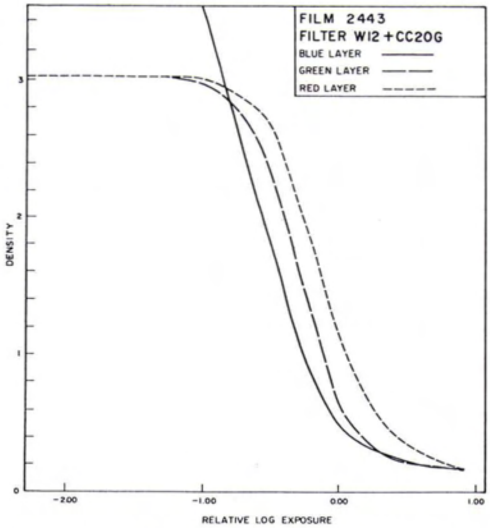


FIG. 9. Sensitometric curve for CC20G test sample.

corresponding standard layer was plotted (Figures 15, 16, and 17). The zero on the ordinate axis represents the standard layer. These plots enable a comparison to be made between each layer with respect to the standard.

Several samples of each filter combination were selected and the middle frame of each stereotriplet was randomly analyzed with the MacBeth densitometer referred to above. One hundred sample points were randomly chosen and a density measurement was made for each of the three layers. The density measurements are a reflection of the degree of transmission allowed by each filter combination. The measurements gave a "quasi-quantitative" estimate of the amount of green, red, and infrared radiation being reflected from the scene (Brooner and Simonett, 1971). By analyzing corresponding frames, compensation for the effects of sun-angle, cloud shadow, vignetting, variations due to terrain reflectances, and differences that may have occurred during processing

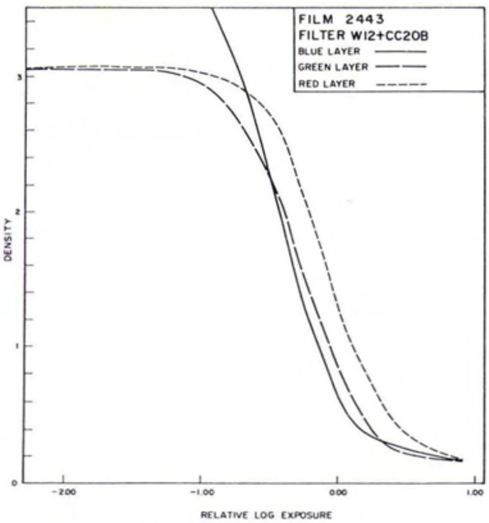


FIG. 8. Sensitometric curve for CC20B test sample.

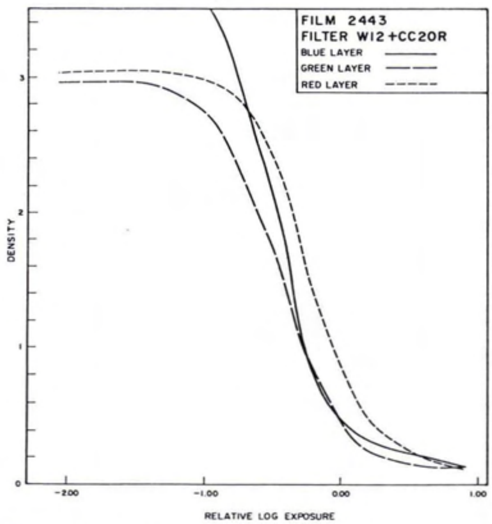


FIG. 10. Sensitometric curve for CC20R test sample.

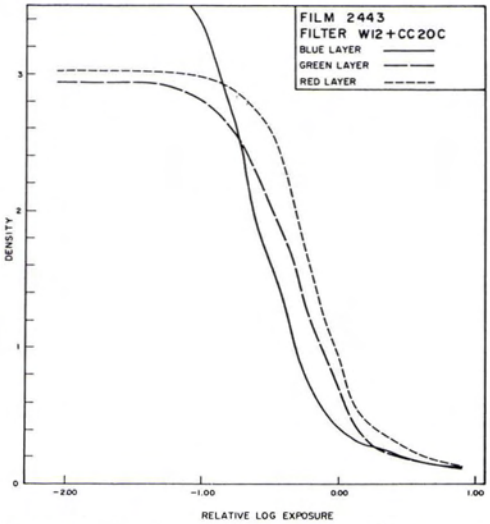


FIG. 11. Sensitometric curve for CC20C test sample.

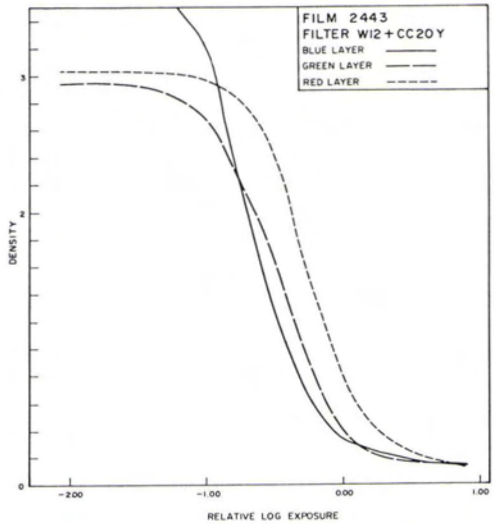


FIG. 13. Sensitometric curve for CC20Y test sample.

were made. Normalizing the density values allows for standardization with respect to the illumination intensity of the densitometer. The density values were normalized using the method of Brooner and Simonett (1971).

The mean, variance, and standard deviation were calculated for the data from each sample frame and results were compared with the W12 standard. Means for each of the layers were compared with the standard and with the average for all sample standards.

The student's "t" test was applied to compare the mean of the sample with the mean of the standard. The test was also applied to the average of all similar CC20___ combinations versus the average of all W12 samples. The statistical analysis was according to Halstead (1966). The "null hypotheses" was stated as: The mean of the sample distribution belongs to the same population as the mean of the standard distribution, i.e., there is no difference between the populations of the two distributions. Comparisons were

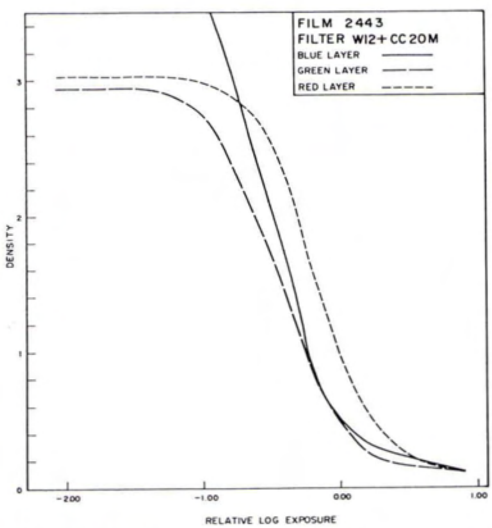


FIG. 12. Sensitometric curve for CC20M test sample.

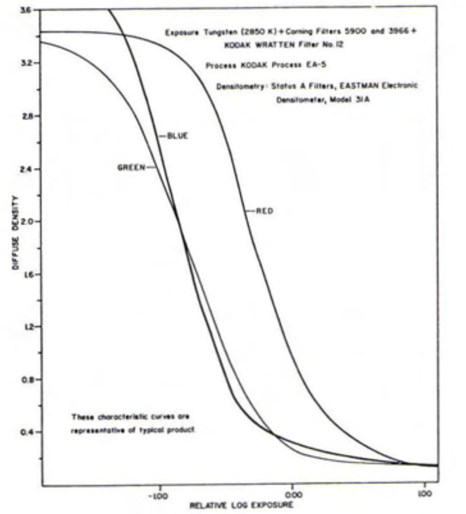


FIG. 14. Theoretical sensitometric characteristic curve for Kodak Aerochrome infrared film 2443 (after Kodak Data for Aerial Photography (M-29), 1971).

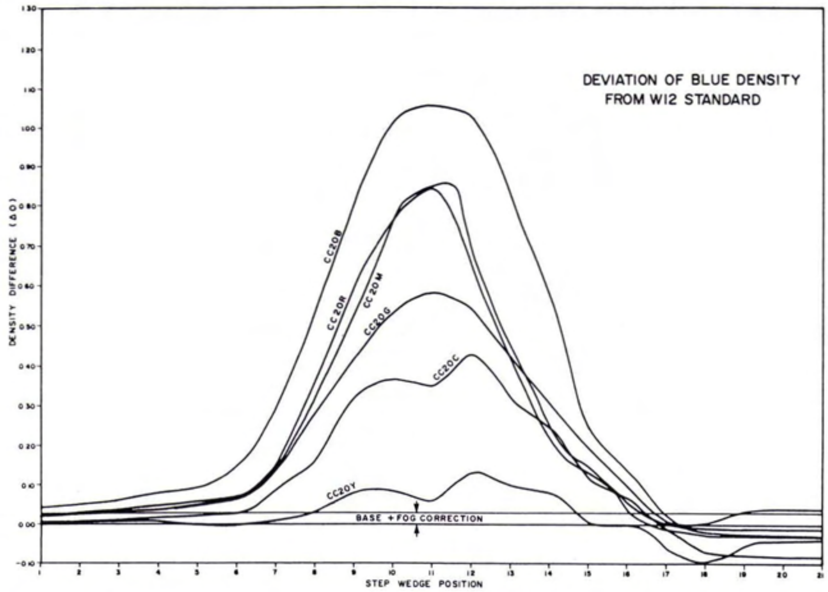


FIG. 15. Curves showing the density difference between the W12 standard wedge and the CC20 combination wedges for the blue film layer.

made between similar color layers only. When the term "distribution" is used it means the distribution of data on one of the three layers and the comparison is made with the same layer of the standard film.

Plates 1, 2, and 3 illustrate two of the sets of sample frames which were analyzed.

RESULTS

In Figures 7, 8, 15, 16, and 17 density increases occur in all three layers with the greatest increase occurring in the blue layer. All three characteristic curves shift to the right (direction of increased density) with the blue and green curves experiencing great-

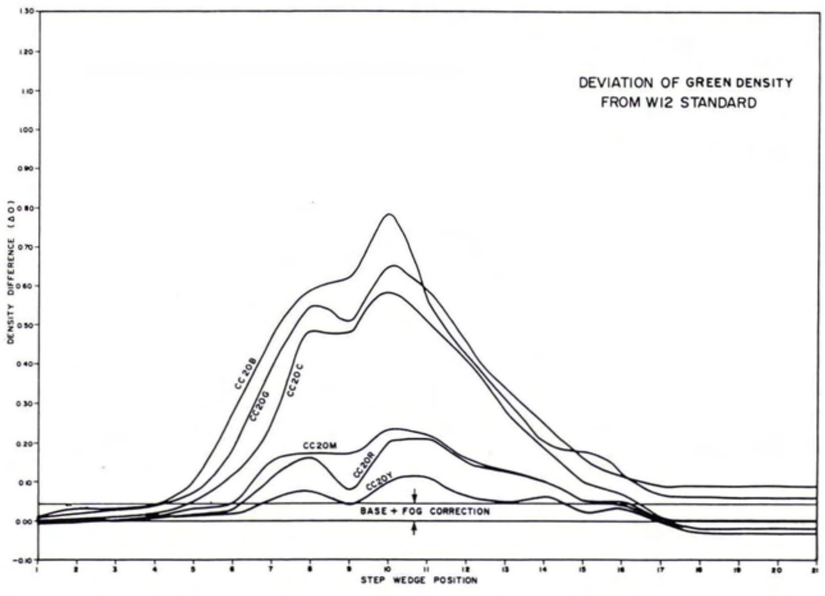


FIG. 16. Curves showing the density difference between the W12 standard wedge and the CC20 combination wedges for the green film layer.

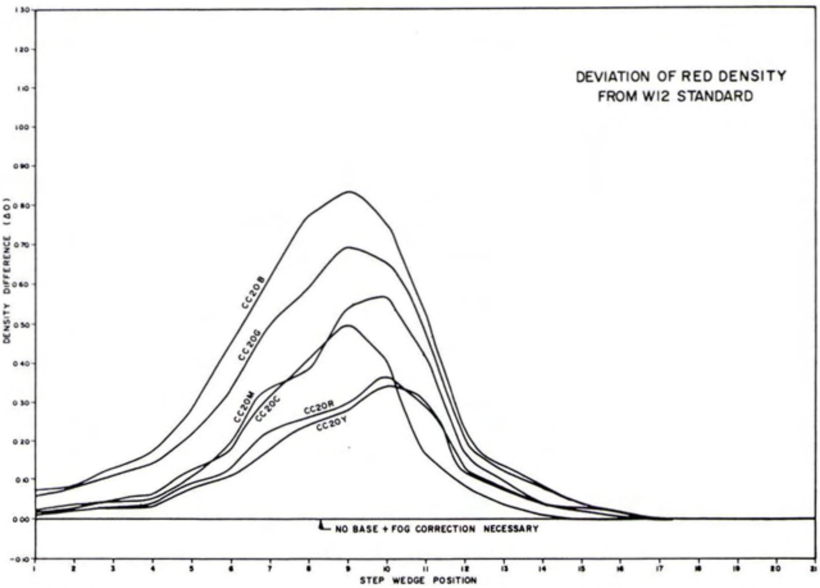


FIG. 17. Curves showing the density difference between the W12 standard wedge and the CC20 combination wedges for the red film layer.

er density increases than the red curve, thus moving closer to the red curve than in the standard. All three layers of the CC20B combination show the greatest increases in Figure 15, 16, and 17.

For the CC20G filters (Figures 7, 9, 15, 16, and 17) density increases occur in all three layers but the green layer shifts the greatest amount in relation to the other two.

For the third set (Figures 7, 10, 15, 16, and 17), the most noticeable shift is shown by the blue curve. The green and red curves show only a small amount of shift when the CC20R is used.

The fourth set is the CC20C combination (Figures 7, 11, 15, 16, and 17). The graphs indicate that the greatest shift occurs with the green curve while the other two curves undergo a small amount of density increase.

The CC20M series (Figures 7, 12, 15, 16, and 17) shows maximum density increase for the blue curve and only a small amount of shift for the green and red.

The last comparison is for the CC20Y combination (Figures 7, 13, 15, 16, and 17). In each of the three layers a small density increase occurs but in all cases the increase is approximately the same and none of the three predominate.

A comparison of Figure 7 with the Kodak Standard (Figure 14) shows that the experimental standard is in good agreement with the Kodak accepted standard. This indicates that the processing procedures were according to Kodak standards, therefore all six filter combinations suitably compare with the Kodak standard.

From these results Table 2 can be constructed showing the order of density increase from the greatest increase to the least increase. The results show that small density increases occur for every layer of the film in every film/filter test where a CC filter was used. Even the CC20Y indicates density increase although the filter does not theoretically affect any spectral region within the range 500—900 nanometres.

The results of the student "t" test for the CC20B filter indicate the blue and Green curves do not belong to the population of the standard, thus indicating that both curves have undergone a density shift. The CC20G curve shows a shift occurring for the green layer, the CC20R for both the blue and

TABLE 2. RANKING OF DENSITY INCREASES ACCORDING TO THE AMOUNT OF DENSITY INCREASE ON EACH LAYER

Blue Density	Green Density	Red Density	
CC20B	CC20B	CC20B	greatest increase
CC20R	CC20G	CC20G	↑
CC20M	CC20C	CC20M	
CC20G	CC20M	CC20C	
CC20C	CC20R	CC20R	↓
CC20Y	CC20Y	CC20Y	least increase

green, the CC20M for the green, and the CC20C for the blue. There is no shift evident for either the blue or green curves for the CC20Y combination. The "t" test at the 95 percent confidence level gives statistical confirmation that use of CC filters significantly changes density distributions.

Discussion

The large density increases that were predicted from the theory and observed using the densitometer analysis of the step-wedges are in agreement with Table 1. For the CC20B filter the blue and green layers undergo a large density increase; the CC20G shows density increase in the green layer; the CC20R in the blue layer; the CC20C in the green layer; the CC20M in the blue layer; and for the CC20Y only minor density increases on any of the three layers. Comparisons with the Kodak Standard (Figure 14) show that the film behaves properly. What was not predictable from the theory was the small density increases in the layers other than the one being attenuated by the selected filter combination.

An examination of Figures 1 to 6 shows that the CC20 filters have an effect in all portions of their spectral band. The attenuation provided by the filter results in a density increase which is shown by a shift of the characteristic curves towards greater density. Each CC20 filter has a spectral region where it attenuates drastically but the characteristic of the curve indicates that because the filters have a diffuse density value throughout the total spectral region, 500—700 nanometres, small density increases should occur in all wavelengths. This accounts for the small density increases that occur on every layer of the film.

Examination of the curve shifts in Figure 8, 9, 10, 11, 12, and 13 show these small density shifts and Figures 15, 16, and 17 show that density increases occur in every layer. Therefore, two density increases are observed using color compensating filters. One density increase is the increase due to the presence of the large diffuse density of the CC filter in a narrow spectral region. This is the expected density increase that can be predicted from the theory. The second increase is due to the CC filter also but it affects all three layers and is caused by the small inherent diffuse density of the filter in all spectral regions and although the diffuse density value is small it is sufficient to block the transmission of radiation in the wavelengths not affected by the large diffuse density values. The second density increase can best be called an attenuation factor because its effect is noted throughout the spectral region of the film. Its value can best be approximated by the density increase of the CC20Y filter combination.

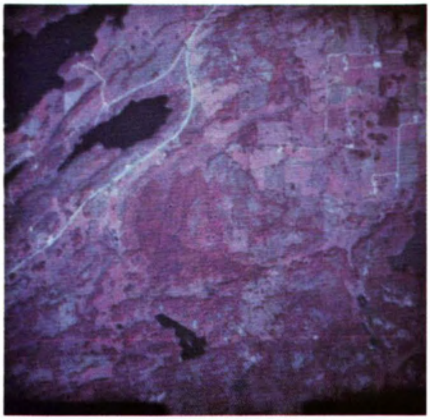
The statistics applied to the test samples are an operational test of the theory. The results of the student's "t" test are in close agreement with the thoretical data. As stated in the "null hypotheses", the test was to see if the mean of the sample distribution belonged to the mean of standard distribution. If the means of the sample distribution did not belong to the mean of the standard distribution, a shift of the characteristic curve had occurred.

For the CC20B both the blue and green layer values indicated that a shift had occurred; therefore, their curves were not part of the same distribution as the standard; hence, a density increase occurred. For the CC20G and CC20M the statistical test showed a shift in the green layer distribution. The CC20R and CC20C show that shifts occurred for both the blue and green curves and for the CC20Y no shifts occurred. The statistics indicated that there were no shifts for any of the red layer distributions.

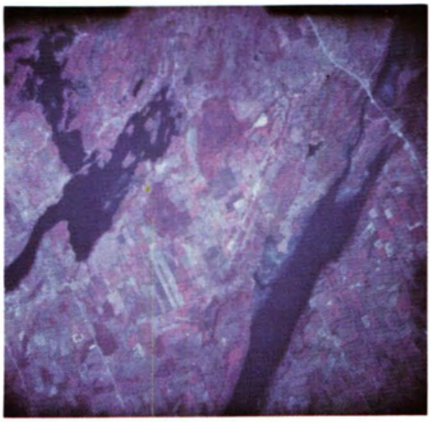
The results indicate close approximation to the theory, but it is felt that not enough data points were observed because there is some evidence of density distribution shift due to the attenuation factor. The CC20R and CC20C both showed shifts for the blue and green, although the theory shows that only the blue should shift with the CC20R and only the green should shift with the CC20C. Also, the experimental evidence indicates that some red shift occurred whereas the statistics did not indicate this shifting.

It can be seen from the results that the step-wedges are necessary for comparison, because they indicate density increases when compared to a test standard and aid in photographic control. The statistical tests must be refined by using a much larger number of randomly oriented test points. This should allow the results to become much closer to the theoretical data of Table 1. The attenuation factor appears in the analysis of all samples and must be included in the analysis because it is still present after the filter factor of the color compensating filters has been adjusted for in exposure. The attenuation factor is caused by the presence of other dye layers in the spectral region that is being attenuated by the filter combination.

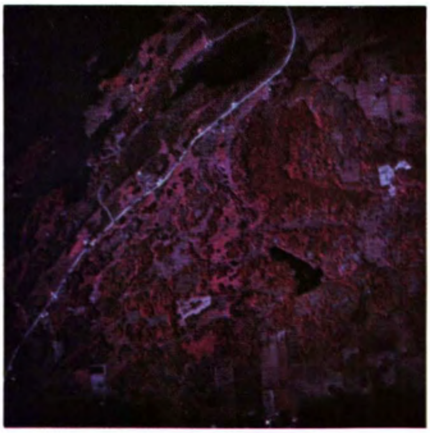
The results of the test show that the blue and green layers of type 2443 film can un-



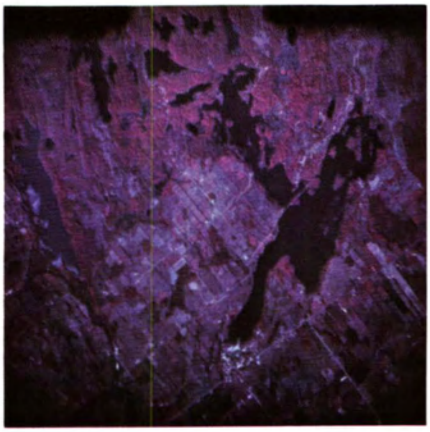
Leo Lake,
W12, 20,000 ft.



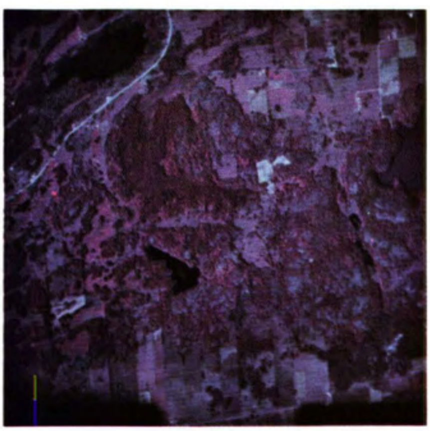
Sydenham Lake,
W12, 40,000 ft.



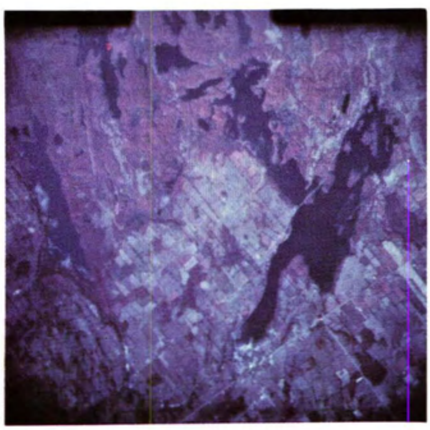
Leo Lake,
W12 + CC20B, 20,000 ft.



Sydenham Lake,
W12, + CC20B, 40,000 ft.

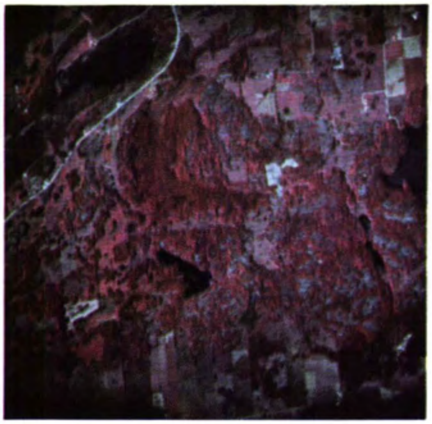


Leo Lake,
W12 + CC20G, 20,000 ft.

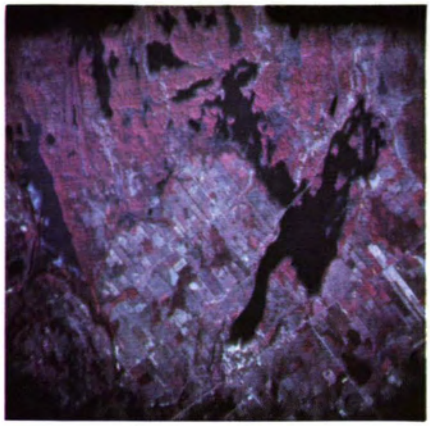


Sydenham Lake,
W12, + CC20G, 40,000 ft.

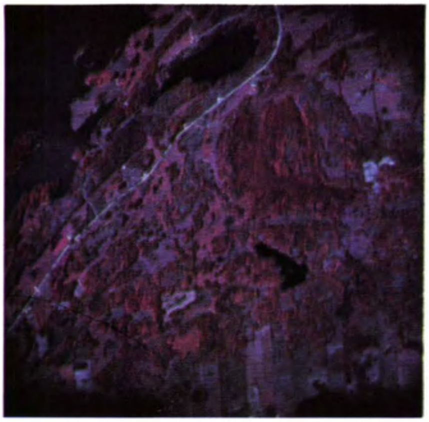
PLATE 1.



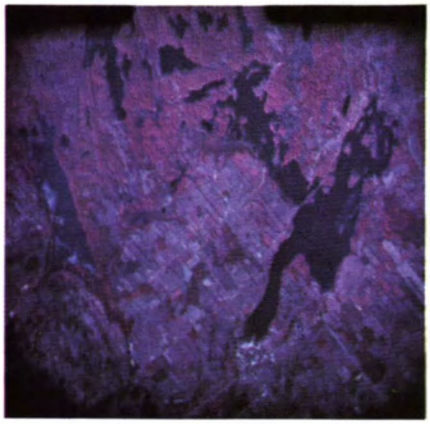
Leo Lake,
W12 + CC20R, 20,000 ft.



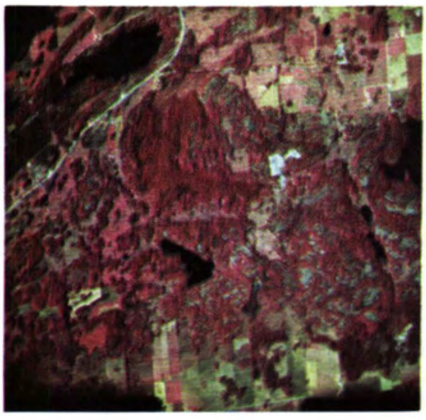
Sydenham Lake,
W12, + CC20R, 40,000 ft.



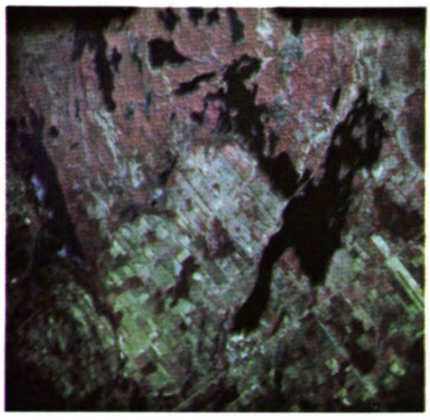
Leo Lake,
W12 + CC20C, 20,000 ft.



Sydenham Lake,
W12, + CC20C, 40,000 ft.



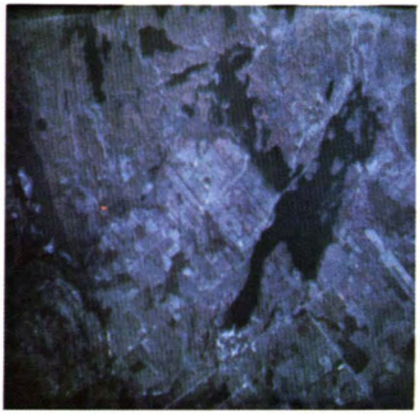
Leo Lake,
W12 + CC20M, 20,000 ft.



Sydenham Lake,
W12, + CC20M, 40,000 ft.

PLATE 2.

Leo Lake,
W12 + CC20Y, 20,000 ft.



Sydenham Lake,
W12, + CC20Y, 40,000 ft.

PLATE 3.

dergo a density increase caused by the presence of a minus visual auxiliary filter. The density increase results in a shift of the characteristic curves towards the red layer curve. An increase in red layer density also occurs but not in the same magnitude as the increases in the other two layers. This indicates that by the use of a greater value of color compensating filter, i.e., CC40B, it should be possible to shift the blue and green curves to such an extent they will become part of the same distribution as the red layer. By doing this, direct comparison measurements can then be made between the three layers on one piece of film. A test standard, W12 only, film will have to be retained for the present so that density shifts can be measured and, in order to indicate proper photographic control of all processes and statistical tests, will have to be performed to insure that film layers in question belong to the same distribution. The use of CCB filters should allow comparisons to be made among all three layers while the CCG, CCR, CCM, and CCC will allow comparisons to be made between the red layer and one other layer. The CCY filter cannot be used because the density increases resulting from its use are not great enough to cause the required amount of shift. The CCY filter may be useful in measuring the attenuation factor.

CONCLUSIONS

From the tests it can be seen that minus visual auxiliary filters are useful in causing density increases in the three layers of type 2443 color infrared film. The color compensating filters were used and each has a specific spectral region where transmission of visual radiation is attenuated. By using the filters, one or both of the blue and green density distributions can be increased in a direction of greater density. The amount of increase will depend upon the value of the filter used. It was found that a second factor was partly responsible for the density increases and hence the shifting of the characteristic curves. This factor has been termed the attenuation factor and it results from the inherent diffuse density of the color compensating filters in the whole spectral range of type 2443. Although its value is small when compared to the density increases due to the increased diffuse density in certain spectral regions caused by the CC filters, its affect is measurable and it shows in the resultant shifting of the spectral curves.

The testing of the step-wedges exposed through the various filter combinations served as a base level to test the theoretical curve shifts. They also indicated the presence of the attenuation factor.

The use of statistics on data derived from operational film served to demonstrate that the density points from each layer could be represented as a distribution and this distribution could be compared to a standard distribution. Therefore, the student's "t" test could be used to determine if the distributions belonged to the same population or another population. By making this comparison, characteristic curve shift (density increase) could be observed mathematically and the shifts described by the statistics could be compared to those described by the theory and demonstrated by the sensitometric tests.

Although a greater number of density points are needed for the statistics, the results indicate that the characteristic curves can be shifted by varying amounts. If the blue and green curves can be shifted so that they are superimposed on the red curve, a second set of statistics could be carried out to affirm that all three curves would belong to a new distribution. To do this, tests should be carried out on greater value color compensating filters, i.e., CC30B or CC40B. Using the CCB filters, it would be possible to superimpose the characteristic curves and then make layer-to-layer spectral measurements on one piece of film. If the CCG, CCR, CCC, or CCM were used, one of either the blue or green curves could be superimposed on the red curve. The CCY filters should be useful to measure the effect of the attenuation factor.

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