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EKIT REPORT NO.10

COMPARATIVE EVALUATION OF EIGHT COLOR MATERIALS

1 AUGUST 1967

CONTRIBUTORS:

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APPROVED BY

[redacted]

GROUP 1

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Itek

ITEK CORPORATION LEXINGTON 73, MASSACHUSETTS

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1. SUMMARY

This report is the tenth in the EKIT series and contains a laboratory evaluation of eight commercially available color materials. Eight color films were selected for the analysis. These films, listed below, are commercially available.

1. Kodachrome II
2. Kodak SO-121
3. Ektachrome High Speed
4. Ektachrome X
5. Anscochrome D/50
6. Anscochrome D/100
7. Agfachrome CT-13S
8. Agfachrome CT-18

Originally, seven films were to be tested. However, shortly after the work started, it was learned that Agfa had marketed a new high resolution film. Its published high contrast resolution was 195 cycles per millimeter. This material was immediately added to the test since its published figure was higher than that of any other commercially available color film.

The analysis of these materials consisted of: (1) a determination of their basic sensitometric and physical characteristics, and (2) a subjective analysis of the images of a model on these films. The results of the materials analysis are shown in the form of several graphs included in Section 2. The curves for the yellow dyes are essentially the same for all of the materials tested. The cyan dye curve, however, varies considerably from one film to the next. It has a very narrow peak in the Kodachrome II in comparison with the other films. The Agfachrome films have their cyan dye peaks shifted toward the near infrared.

The spectral sensitivities of these materials are also shown. The one material that is significantly different from the others is SO-121. The green sensitive record has more than the usual amount of sensitivity in the blue region of the spectrum. The other films have a yellow filter layer (that effectively removes the inherent blue sensitivity of the other layer) below the blue sensitive layer. However, since SO-121 has the magenta layer on the top, it cannot make use of the yellow filter mechanism. The inherent blue sensitivity of the green layer must be controlled by other means, i.e., by a chemical desensitization. This means that in terms of aerial photographs it is difficult to reproduce a blue object as blue. The object will also have some green in it, and therefore look cyan.

The resolutions of these materials vary considerably from one film to the next. The highest resolution film was found to be Kodachrome II, with Agfachrome CT-13S a close second. SO-121 ranks next with about 30-percent lower high contrast resolution and 10-percent lower low contrast resolution than Kodachrome II.

The subjective analysis of model photography with these materials again indicates that Kodachrome II is the best material for overall image quality. The difference between SO-121 and Agfachrome CT-13S is very slight, with the Agfachrome having a slight edge.

Kodachrome II appears to be the best color film of the eight as far as their image quality is concerned. One of the most difficult problems with this material, though, will not be in using the material in the camera but in the processing of the film. It can be commercially bought in 70-millimeter widths for use in the camera, but the only Kodachrome II processing machines in existence today are for 35-millimeter amateur films. A limited test can be run, though, on mission photography if the film is split into two 35-millimeter widths for processing.

2. MATERIALS ANALYSIS

The major portion of this analysis took the part of an investigation into the physical properties of the eight materials under test. The data generated from most of these tests could have been supplied by the manufacturers. However, since there were three film manufacturers involved (Eastman Kodak, General Analine and Film, and Agfa) the data would have come from three independent sources. Since the measurement of these characteristics of color film is subject to many sources of error, such data could make an accurate comparison quite difficult. With the analysis performed in only one laboratory, such differences would be considerably reduced. Though these same errors probably exist in the tests performed in these laboratories, the errors at least result from the same source, and are therefore consistent among the films.

The physical analysis of these films consisted of determining their basic characteristics:

1. The spectral densities of the dyes
2. The constants for converting integral spectral density to equivalent neutral density
3. Equivalent neutral density curves
4. Spectral sensitivity
5. Resolution

Preceding each of the sections is a description of the manner in which these characteristics were measured at Itek, the manner in which the manufacturer measures them, their meaning, and their function in the color film.

Some of the techniques used in these analyses are very old; some have been developed quite recently, in particular, from a recent contract with Wright-Patterson Avionic Laboratories (Air Force Contract No. [redacted] This effort resulted in a Color Tone Reproduction Theory and Practice Manual which describes many of the fundamental concepts of color theory.

2.1 DYE CHARACTERISTICS

All the color films are constructed so that cyan, magenta, and yellow dye layers form the final color image. The three dye layers are positioned one on top of the other on one side of a transparent film base. Each layer acts independently to record the red, green, and blue components to the scene by varying the amounts of the cyan, magenta, and yellow concentrations contained in its particular layer. Cross sections of the individual films are discussed in Section 2.5. Notice that not all of the films have the same dye layer orientation. The one unusual film is SO-121 which has the magenta instead of the yellow layer on top.

To properly measure the density of any color film, a densitometer must be obtained which has the proper red, green, and blue filters for reading the cyan, magenta, and yellow dye densities. Unlike black and white photography where a neutral, spectrally flat, silver image is measured, color films contain a cyan, magenta, and yellow dye layer for controlling the red, green, and blue

light of the visible spectrum. Dye layers cannot be measured separately unless they are physically separated. This separation is very difficult if not impossible to accomplish. The manufacturer, however, has the opportunity to coat only one of the layers at a time to obtain his samples for measurement.

Dye separations were obtained by fogging out two of the layers, leaving a pure dye in the third. After the three pure dye samples were obtained, they were traced on a spectrophotometer using a clear film sample in the reference beam. Each dye curve was normalized to its peak density and plotted. The curves represent the analytical spectral density curves of the individual films. Once normalized, the three curves for each film were added together to obtain integral spectral density curves which are also shown in the illustration in Fig. 2-1.

To determine the sensitometric response of a color film, it is necessary first to determine the spectral densities of the individual dyes. Since each dye has a fairly sharp peak, density measurements obtained are a function of the peak transmission and bandwidth of the filter used in the densitometer. Also shown in Fig. 2-1 are the effective blue, green, and red responses of the MacBeth TD-102 densitometer that was used for reading each of the eight films. The filters must be adjusted for each particular set of dyes so that the readings are always taken at the peaks.

Wratten and interference filters that had peak transmissions close to the peak densities of the dyes were chosen. The red, green, and blue densitometer responses are shown for each of the filters used. The plotted curves were found by multiplying the filter transmission curves together with the spectral emittance curves of the densitometer lamp, infrared rejection filters, and photomultiplier response. The infrared filter was not used for the Agfa films due to the need to measure the cyan peak with a 7.06-nanometer interference filter.

The dye curves of the various films are significantly different. This is noticed mainly in the cyan curves. The cyan peak of Kodachrome II is at about 640 nanometers, while the cyan peak of Agfachrome CT-18 is at about 690 nanometers, a 50-nanometer shift toward the infrared. In all cases the yellow dyes are almost identical. The Kodachrome II cyan dye is considerably narrower in bandwidth than the remaining dye curves.

It is evident from the curves that it is very important to use the proper densitometer filters with a given film. Failure to pick the proper filter will result in low densities that do not represent the true response of the dye. The density readings with these filters form the basis of most of the remaining analysis.

2.2 ISD TO END EQUATIONS

When density measurements are made with a laboratory densitometer, the resulting values represent the total effect of the three layers of the color film on a transmitted beam of light. These densities are called integral spectral densities (ISD's). It is possible, by use of the proper equations, to convert these ISD's to equivalent neutral densities (END's), which describe each individual dye layer's visual characteristics.

The densitometer used for illustration in this report was a MacBeth Quantalog Model TD-102 equipped with a special adapter in the base for holding interference filters. The filters used for each of the evaluated films were listed in Table 2-1 and illustrated in Fig. 2-1.

If there were no overlap in the absorption of the dye curves, the equivalent neutral density would be a very simple function of the integral spectral density in the wavelength required dye. With no overlap the equation would be:

$$CEND = 1.0DR - 0.0DC - 0.0\,DB$$

$$MEND = 0.0DR + 1.0DG - 0.0DB$$

$$YEND = 0.0DR - 0.0DG + 1.0DB$$

where CEND, MEND, and YEND are the cyan, magenta, and yellow equivalent neutral densities and DR, DG, and DB are the red, green, and blue integral spectral densities.

Since there is an overlap, the equation takes the same form although there are values in the place of the six zeroes above.

The procedure involved in determining these equations is based upon the dye curves themselves.

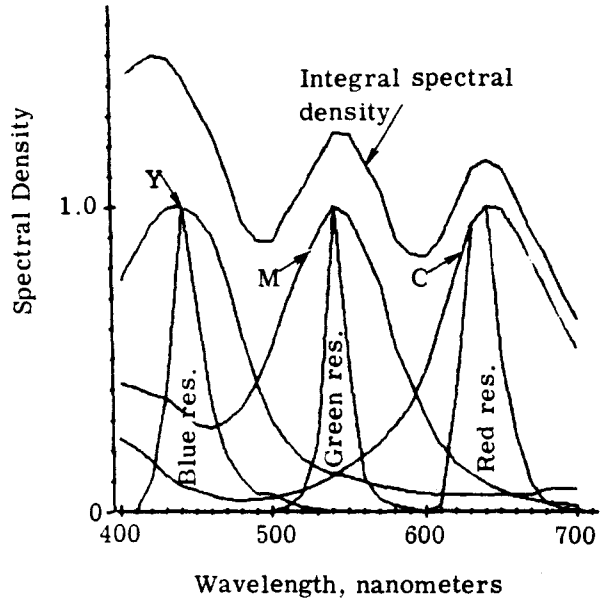
The procedure involves making a stepped exposure in one of the records while essentially destroying all of the dyes in the other two layers. Although this is impossible to do over the step range, it can normally be done quite satisfactorily over half of that range. These colored step wedges (one cyan, one magenta, one yellow) are then read with the narrow band red, green, and blue filters previously discussed. The densities of one set of readings (i.e., green and blue readings of the same cyan strips) are plotted against the density values of the two other density readings. The slope of these lines then represents the degree of overlap and is, therefore, used in the one of the three equations relating the END's to the ISD's. The same procedure is followed for the remaining two strips to complete the two other equations.

Table 2-2 lists these equations for the eight materials when used with the particular densitometer filters listed in Table 2-1.

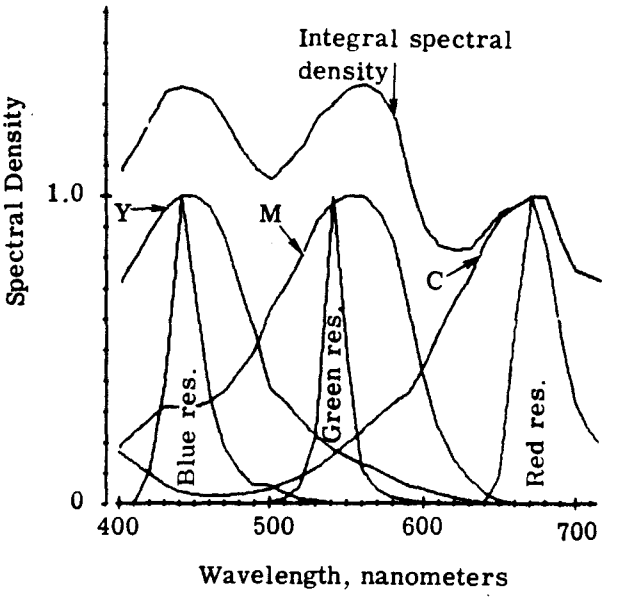
2.3 EQUIVALENT NEUTRAL DENSITY CURVES

With normal black and white emulsions, there is a single relationship between the response (density) and the input (log exposure). With color materials, however, there are actually three emulsions within the same film, each recording a separate response. The best method for describing these three emulsions is by three characteristic curves that independently describe each layer. The procedure is to make a neutral strip in the laboratory and measure the integral spectral densities of the 21 steps. These data are then converted to equivalent neutral densities by the equations described in Section 2.2. It is often difficult to obtain a neutral strip over the entire log exposure range. In fact, generally speaking, it is impossible to do so. For these cases, the analysis techniques developed require only that a single step near a density of 1.0 be neutral. Fig. 2-2 illustrates the END curves for the eight films. The curves were determined by producing a near neutral sensitometric step and reading the ISD's of the step. These were then converted to END's by the appropriate equation.

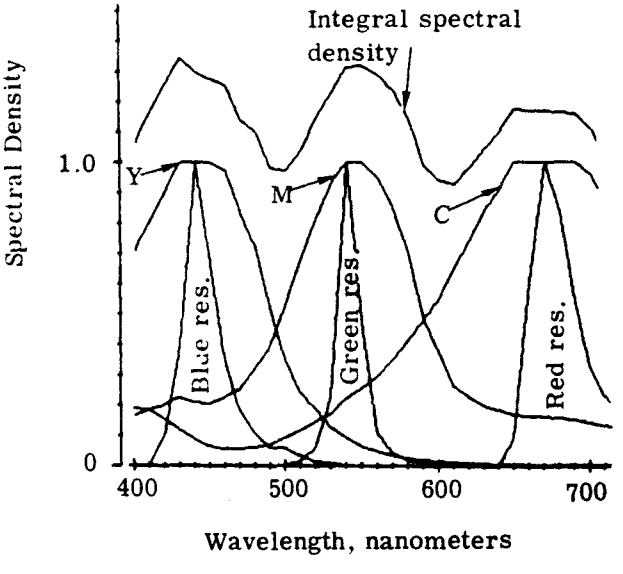
Where the curves overlap, the amount of dye that is present in each of the individual layers produces a neutral when combined with the proper amount of dye in the other two layers. Since the curves describe the dyes and do not include the base plus stain, they level out at zero density in the D_{min} area.



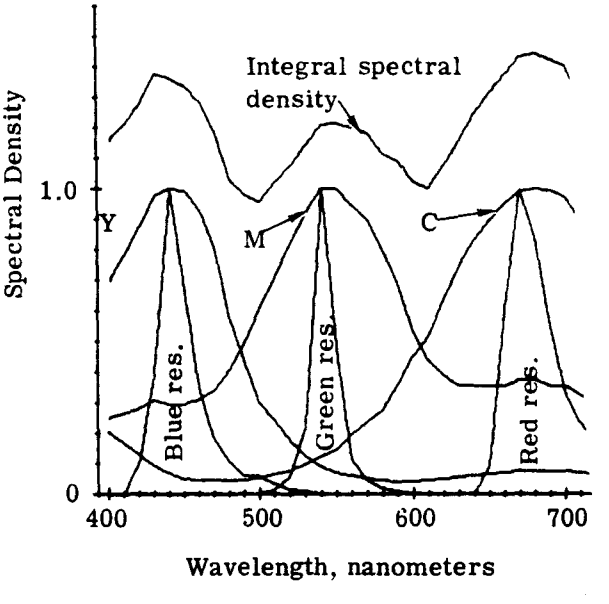
a. Kodachrome II



b. Kodak SO-121

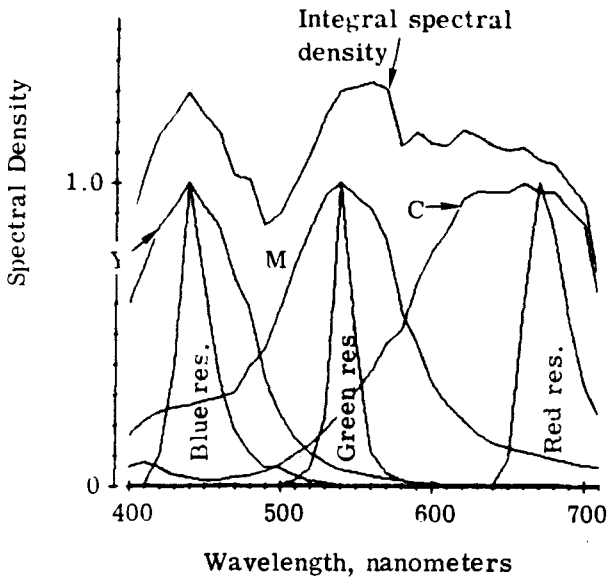


c. Ektachrome High Speed

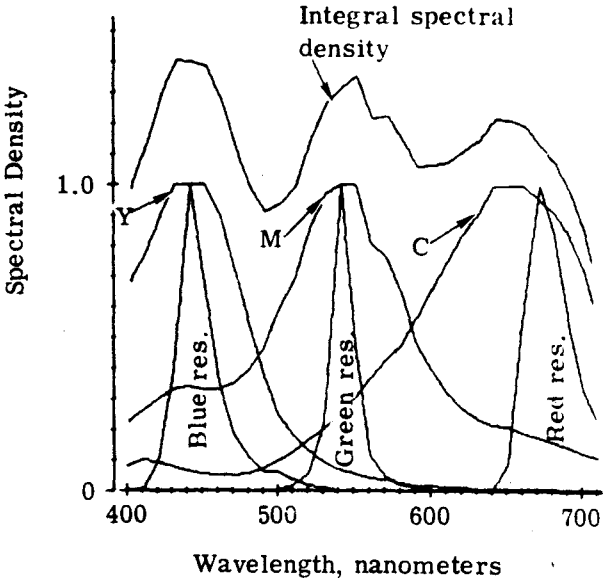


d. Ektachrome X

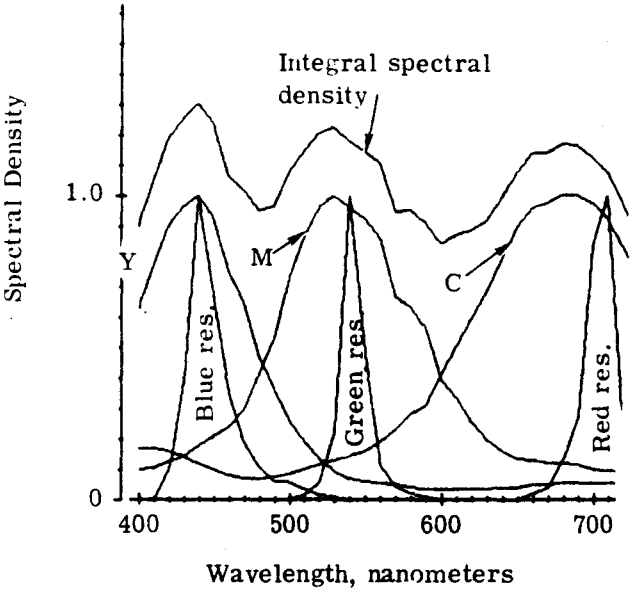
Fig. 2-1 — Normalized spectral density curves



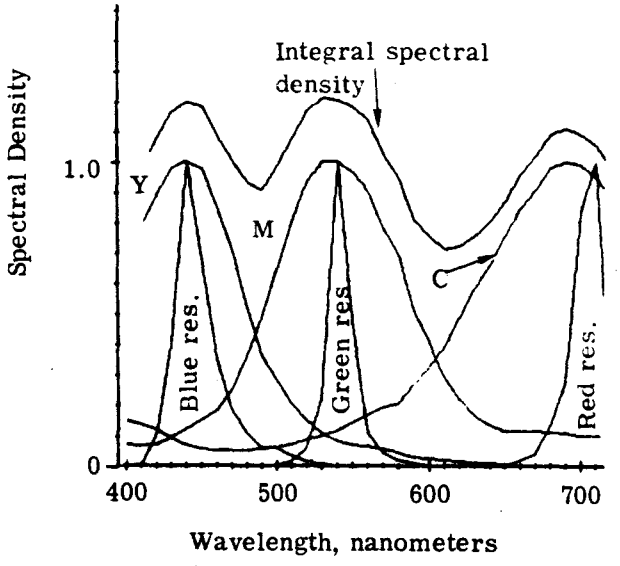
e. Anscochrome D/50



f. Anscochrome D/100



g. Agfachrome CT-13S



h. Agfachrome CT-18

Fig. 2-1 — Normalized spectral density curves (Cont.)

Table 2-1 — Wratten and Interference (INT) Filters Used in the Densitometer

Kodachrome II

Red: Two Wratten 29
Green: Wratten 99 + INT 546
Blue: Wratten 94 + INT 435

Kodak SO-121

Red: Wratten 70
Green: Wratten 99 + INT 546
Blue: Wratten 94 + INT 435

Ektachrome High Speed

Red: Wratten 70
Green: Wratten 99 + INT 546
Blue: Wratten 94 + INT 435

Ektachrome X

Red: Wratten 70
Green: Wratten 99 + INT 546
Blue: Wratten 94 + INT 435

Anscochrome D/50

Red: Wratten 70
Green: Wratten 99 + INT 546
Blue: Wratten 94 + INT 435

Anscochrome D/100

Red: Wratten 70
Green: Wratten 99 + INT 546
Blue: Wratten 94 + INT 435

Agfachrome CT-13S

Red: Wratten 70 (no IR filter)
Green: Wratten 99 + INT 546
Blue: Wratten 94 + INT 435

Agfachrome CT-18

Red: Wratten 70 (no IR filter)
Green: Wratten 99 + INT 546
Blue: Wratten 94 + INT 435

NOTE: All filter combinations include an infrared rejection filter unless otherwise stated.

Table 2-2 — Integral Spectral Density (ISD) to Equivalent Neutral Density (END) Equations for Eight Color Materials

Kodachrome II

CEND = 0.962DR - 0.094DG - 0.014DB
MEND = -0.171DR + 1.177DG - 0.117DB
YEND = -0.043DR - 0.024DG + 1.011DB

Kodak SO-121

CEND = 0.930DR - 0.048DG - 0.005DB
MEND = -0.368DR + 1.554DG - 0.234DB
YEND = -0.007DR - 0.325DG + 1.216DB

Ektachrome High Speed

CEND = 1.209DR - 0.364DG + 0.019DB
MEND = -0.201DR + 1.306DG - 0.112DB
YEND = 0.022DR - 0.347DG + 1.230DB

Ektachrome X

CEND = 1.120DR - 0.308DG - 0.058DB
MEND = -0.164DR + 1.113DG - 0.083DB
YEND = -0.003DR - 0.350DG + 1.220DB

Anscochrome D/50

CEND = 1.227DR - 0.111DG - 0.001DB
MEND = -0.490DR + 1.420DG - 0.067DB
YEND = 0.056DR - 0.389DG + 1.328DB

Anscochrome D/100

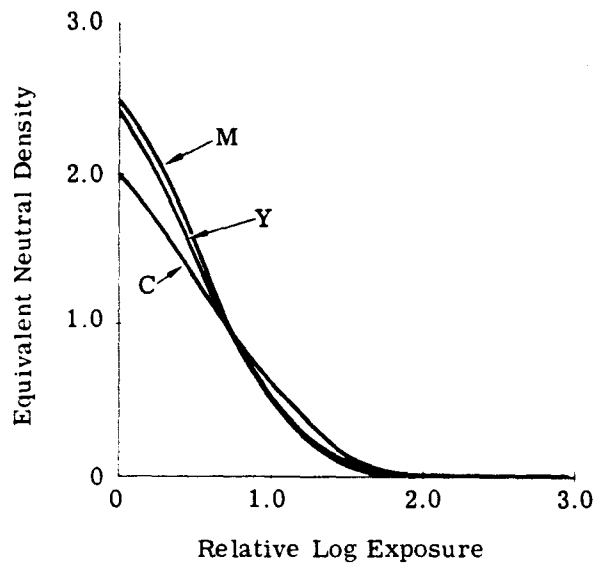
CEND = 1.300DR - 0.166DG - 0.001DB
MEND = -0.676DR + 1.705DG - 0.126DB
YEND = 0.057DR - 0.446DG + 1.239DB

Agfachrome CT-13S

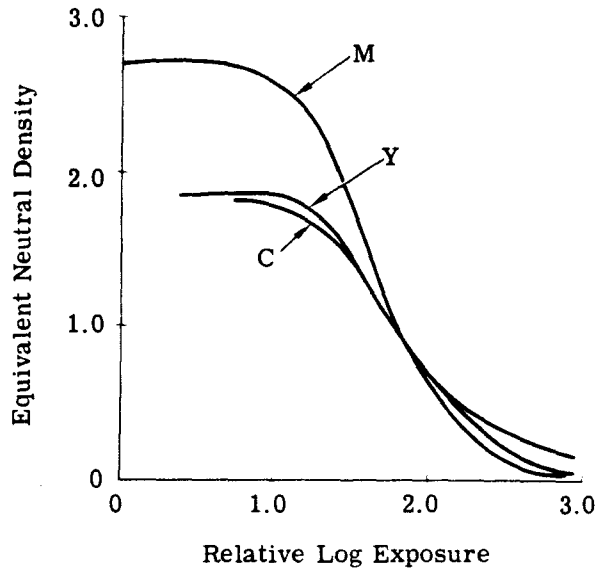
CEND = 0.619DR - 0.022DG - 0.005DB
MEND = -0.257DR + 1.544DG - 0.044DB
YEND = -0.161DR - 0.484DG + 2.024DB

Agfachrome CT-18

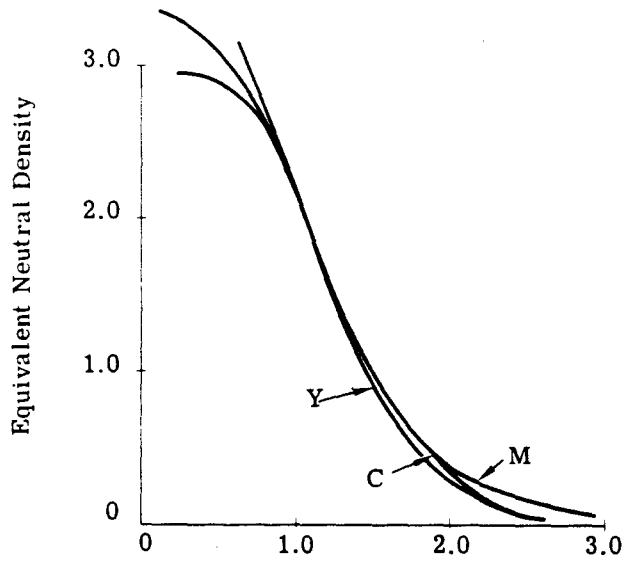
CEND = 0.615DR - 0.084DG + 0.003DB
MEND = -0.672DR + 2.396DG - 0.245DB
YEND = 0.021DR - 0.363DG + 1.538DB



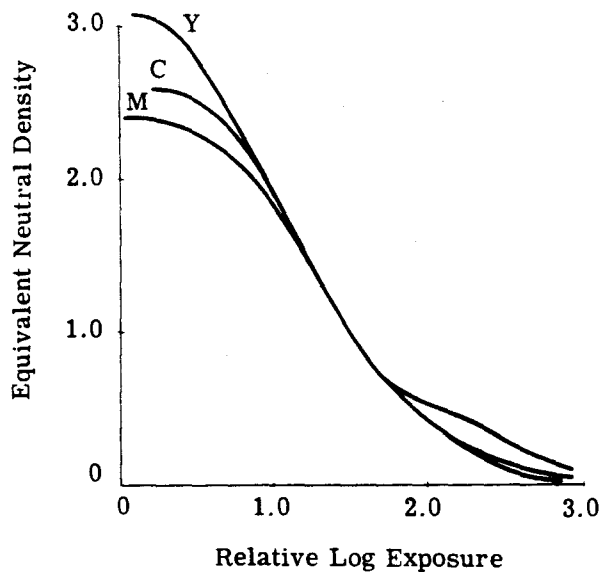
a. Kodachrome II



b. Kodak SO-121

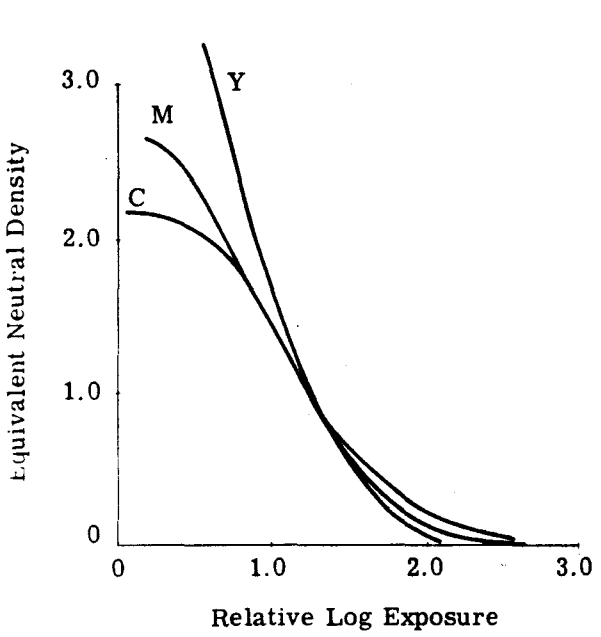


c. Ektachrome High Speed

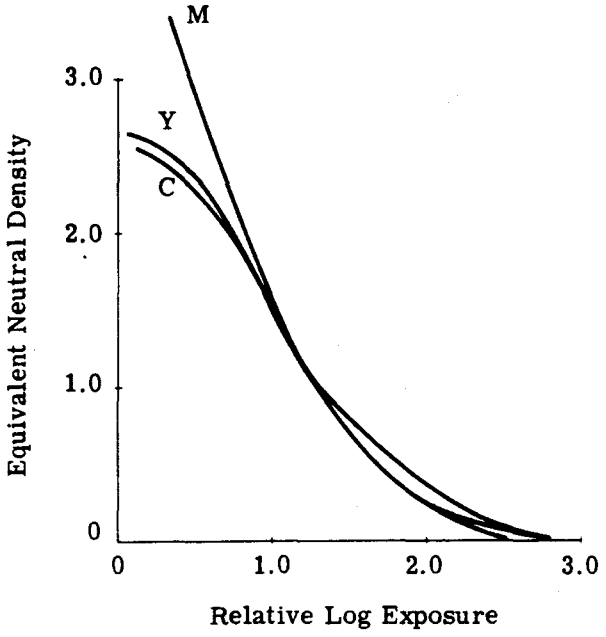


d. Ektachrome X

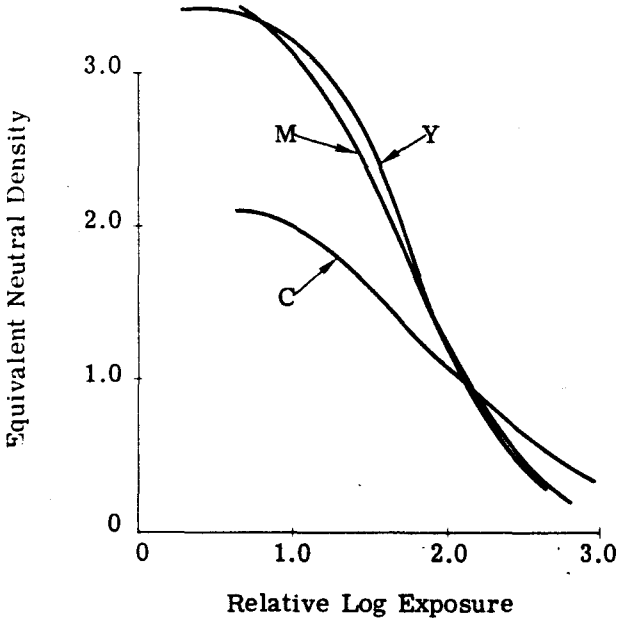
Fig. 2-2 — END's (equivalent neutral densities) calculated for the neutral strip



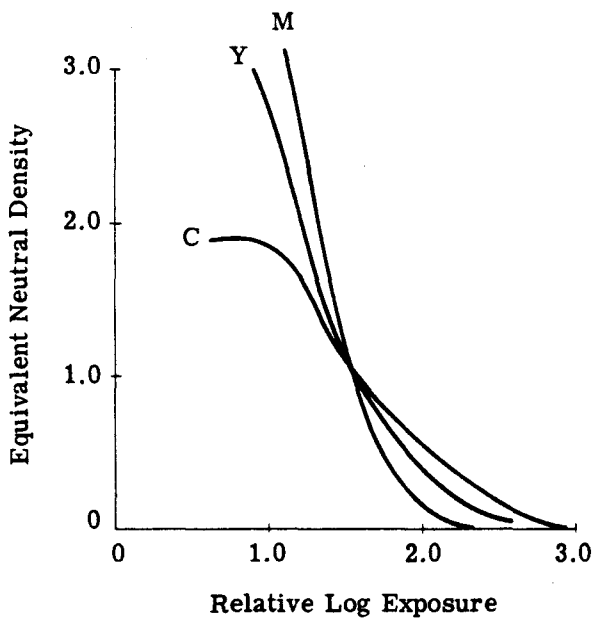
e. Anscochrome D/50



f. Anscochrome D/100



g. Agfachrome CT-13S



h. Agfachrome CT-18

Fig. 2-2 — END's (equivalent neutral densities) calculated for the neutral strip (Cont.)

Much information can be derived from the curves for the eight films. The gammas of an individual film can be compared to determine the film's contrast in each of the sensitive layers. By comparing the different films together, it is possible to determine which are inherently higher in contrast. The additional contrast may be more advantageous for use in reconnaissance photography to compensate for haze unless the limited latitude of the high contrast film is a disadvantage.

Many of the films do not reproduce neutrals over their entire range. This may be due either to problems in processing or to characteristics designed into the film. The indicated shifts in color balance in the highlights and shadow areas correspond to color casts seen in the static model tests of Section 3.

The gammas at a 1.0 END level are given for the three dye layers for all eight films in Table 2-3. In general, most of the films have about the same contrast. Ektachrome High Speed and the Agfachrome films are of higher contrast, but the Agfachrome films have cyan layers that are very different from the other layers.

2.4 SENSITIVITY AND SPEED

The three layers of a color film normally record from top to bottom the blue, green, and red regions of the spectrum. Each sensitive layer usually has a fairly broad band sensitivity to its region of the spectrum and therefore integrates the spectral information over about one third of the visible spectrum. The response of each layer to the exposing radiation is measured by the amount of dye that remains after processing.

Since the evaluated films are all of the reversal type, the more exposure each film receives, the less dye remains in the processed material. Sensitivity is given as the reciprocal of that amount of energy required to yield a certain density. Therefore, the greater the sensitivity, the less exposure is required to produce this certain density. The equivalent neutral density used for specifying spectral sensitivity for reversal films is normally 1.0. The eight films and their listed ASA film speeds are given in Table 2-4.

The spectral sensitivity curves in Fig. 2-3 were obtained by exposing sensitometric strips to narrow band interference filters and processing them according to the manufacturers' instructions.

These strips were then read with a densitometer to determine the integral spectral densities for each of the 21 steps. The equations in Section 2.2 were then used to solve for the cyan, magenta, and yellow END curves. Since spectral sensitivity at a given wavelength is defined as the reciprocal of the energy required to produce an END of 1.0, these energy values were found by interpolating back through the END curves at an END of 1.0. The reciprocal of this (log) exposure is then the sensitivity at the spectral region of the filter used to make the sample. The laboratory work was carried out with 10 of these interference filters that covered the wavelength region of 400 to 700 nanometers. In some cases, there were rather large wavelength regions where no filter was available. In order to obtain a smooth curve from these data points, the manufacturer's data were used as a guide for areas of uncertainty.

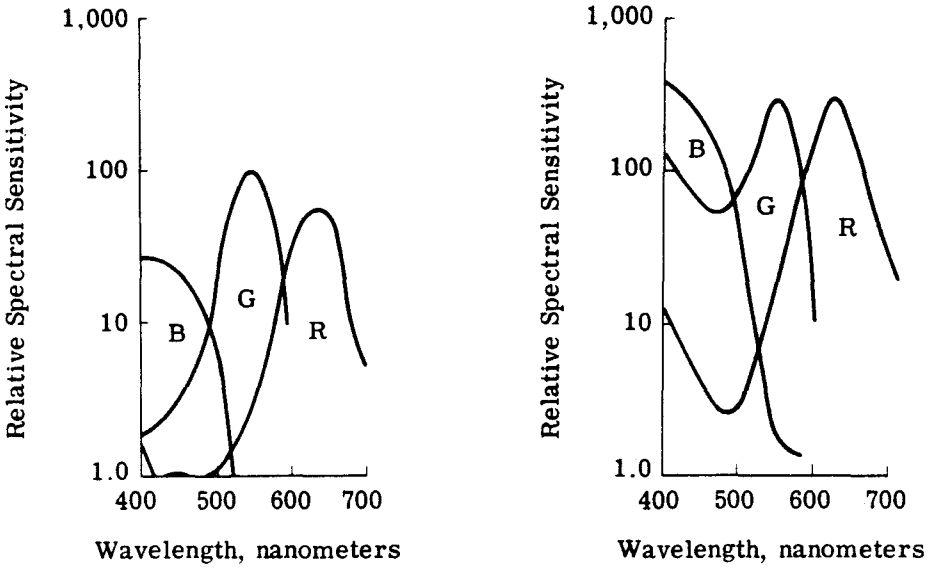
The shapes of the spectral sensitivity curves are generally the same for all the films except SO-121. This film does not have the yellow filter layer between the top and middle layers as do the other seven films. The yellow filter layer is used to prevent blue radiation from penetrating to the bottom two layers and is removed during the bleaching step of the process. In addition, the SO-121 has a layer orientation that is different from the classical order of the other films.

Table 2-3 — Cyan, Magenta, and Yellow Gammas for the END Curves of the Eight Color Films

	Cyan γ	Magenta γ	Yellow γ
Kodachrome II	1.45	2.00	1.68
Kodak SO-121	1.31	2.25	1.54
Ektachrome High Speed	1.80	2.26	2.00
Ektachrome X	1.67	1.50	1.56
Anscochrome D/50	1.25	1.56	1.71
Anscochrome D/100	1.35	2.00	1.40
Agfachrome CT-13S	1.02	1.90	2.20
Agfachrome CT-18	1.26	3.00	2.50

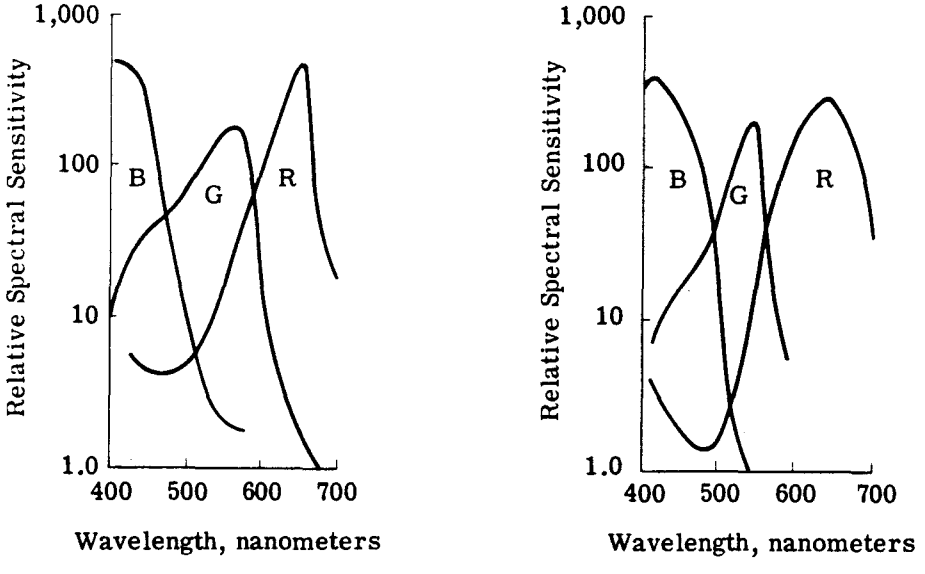
Table 2-4 — ASA Equivalent Speeds for the Eight Color Films

	ASA Film Speed
Kodachrome II	25
Kodak SO-121	64
Ektachrome High Speed	160
Ektachrome X	80
Anscochrome D/50	50
Anscochrome D/100	100
Agfachrome CT-13S	16
Agfachrome CT-18	40



a. Kodachrome II

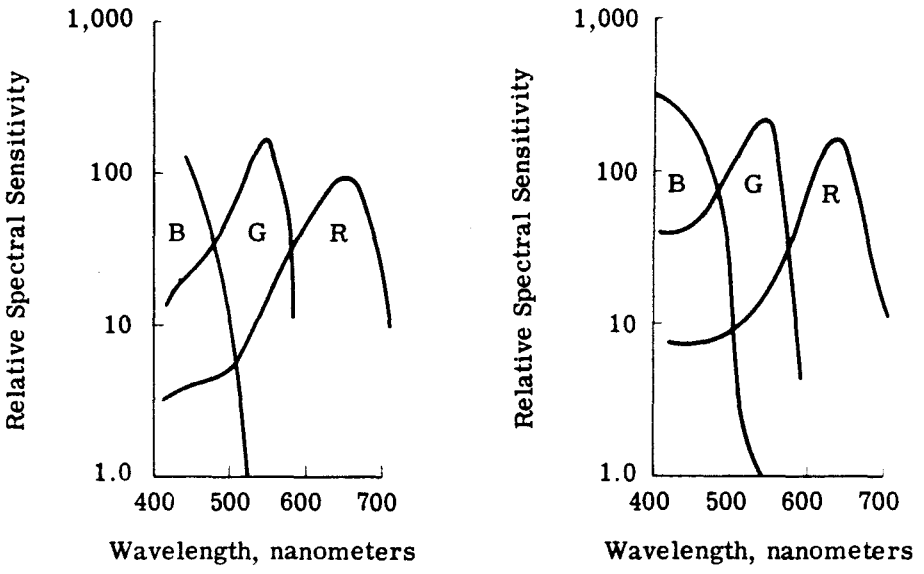
b. Kodak SO-121



c. Ektachrome High Speed

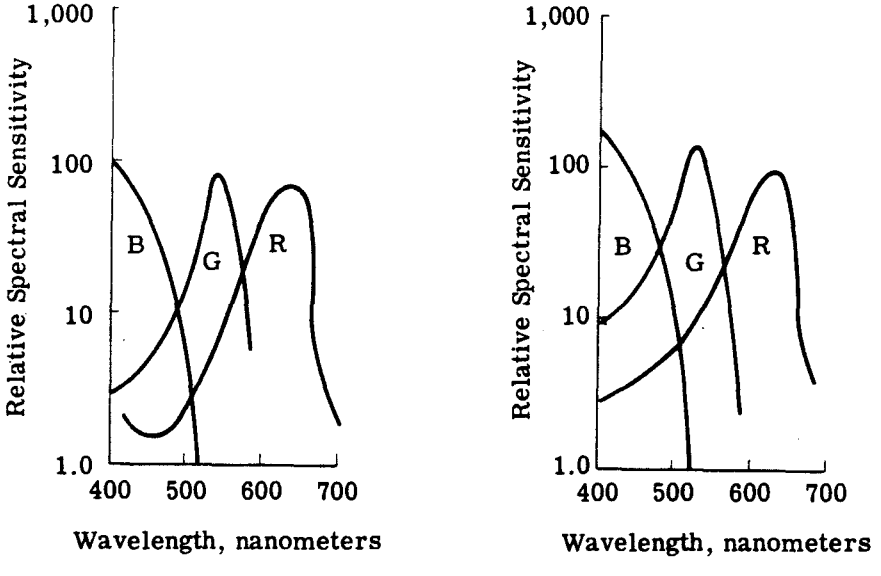
d. Ektachrome X

Fig. 2-3 — Spectral sensitivity curves



e. Anscochrome D/50

f. Anscochrome D/100



g. Agfachrome CT-13S

h. Agfachrome CT-18

Fig. 2-3 — Spectral sensitivity curves (Cont.)

The green sensitive layer is on the top with the blue sensitive layer just below it. The classical order for the layers is the yellow on top followed by the magenta and then the cyan. The orientation in the SO-121 allows the magenta dye layer, which contains the greatest visual details, to be on the surface of the film where there is less scattering to degrade the image.

Without the yellow filter layer, the magenta forming layer of the SO-121 shows a high sensitivity to blue light [see Figs. 2-3(b) and 2-4(c)]. With a proper short wavelength blocking filter such as the Wratten nos. 2E or 4, it is possible to get sufficient separation between the green and blue records to produce good image.

2.5 RESOLUTION AND MICROTOMES OF THE FILMS

The Itek Mark III resolving power camera was used to determine the resolving power of the eight color materials. The camera has been qualified by the proposed ASA standard on resolving power for black and white emulsions. Table 2-5 gives the average resolution for each of the materials at a high and low test object contrast. All processing was done in these laboratories according to the manufacturer's instructions except for the Kodachrome II which was processed by [redacted]

The results of this test indicate that Kodachrome II and Agfachrome CT-13S have the best high contrast resolving power, with the Kodachrome II better at the lower contrast. Eastman Kodak SO-121 has the next best high and low contrast resolution followed by Ektachrome X. Next in line are the two Anscochromes, with Ektachrome High Speed having the lowest resolving power.

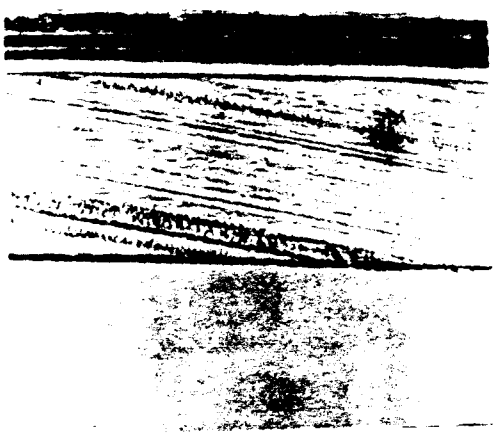
In order to obtain a better understanding of the construction of these color films, microtomes were made of unexposed processed samples. Since the samples are unexposed, the dye concentrations are high and easily seen (Fig. 2-4). These microtomes are approximately 2.5 microns thick and are enlarged approximately 350 times.

The buckling on the top layer of the Kodachrome II is probably due to the microtome blade's shattering the lacquer finish that is put on the film at the end of processing. The thin base of the SO-121 sample is evident in Fig. 2-4. Note also that the magenta and yellow dye layers have been reversed with SO-121. There is also a coating, probably gelatin, on the back side of the base, which is used as a support for the peloid crystals and as an anticurl mechanism for the film. With gelatin on the back of the film, its inherent curl when drying counters that of the emulsion, thus preventing the materials from rolling up like a spindle.

One should not put too much emphasis on the exact colors of the dyes in these images. The yellow dye, for example, in the two Ektachromes looks quite similar, but together quite different from the two Agfachrome yellow dyes. The dye curves presented in Figs. 2-1(c), 2-1(d), 2-1(g), and 2-1(h) indicate that there is actually very little difference between them. The color in these photographs are subject to the limitation of the color print material the optics involved in making the microphotographs, and in the variation in thickness of the microtomes themselves. It is interesting to see how thick the dye layers of the Anscochrome films are in comparison with the remainder of the films. This is probably a large part of the reason for the low resolution of this material.

a. Kodachrome II

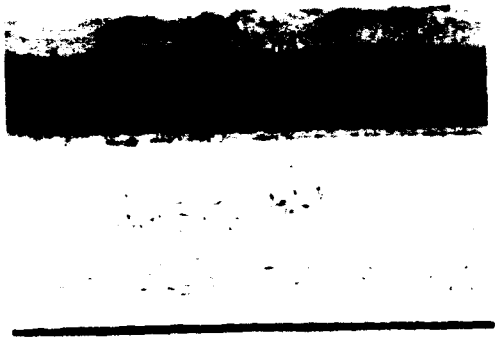
b. Kodak SO-121



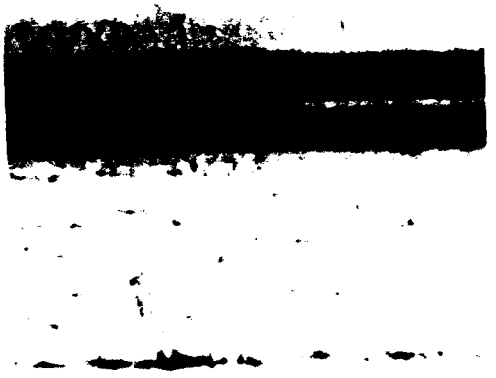
c. Ektachrome High Speed

d. Ektachrome X

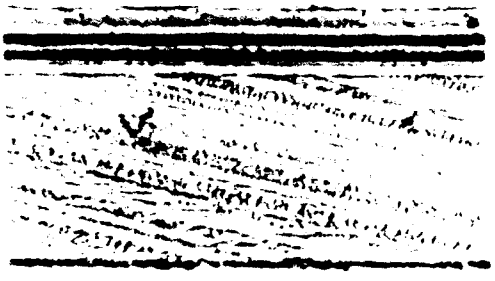
Fig. 2-4 — Microtomes (350×)



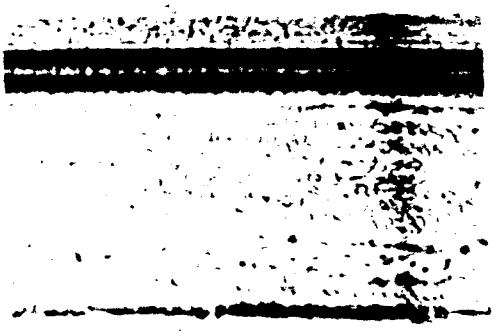
e. Anscochrome D/50



f. Anscochrome D/100



g. Agfachrome CT-13S



h. Agfachrome CT-18

Fig. 2-4 — Microtomes (350×) (Cont.)

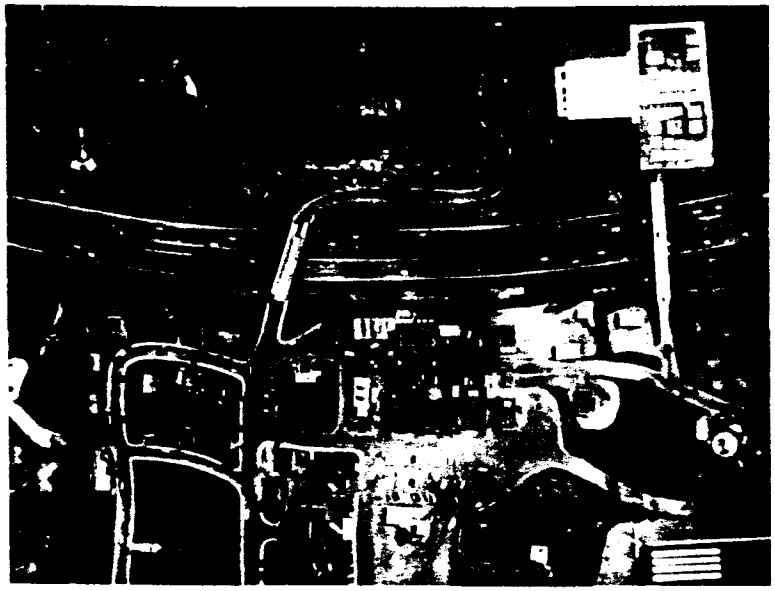
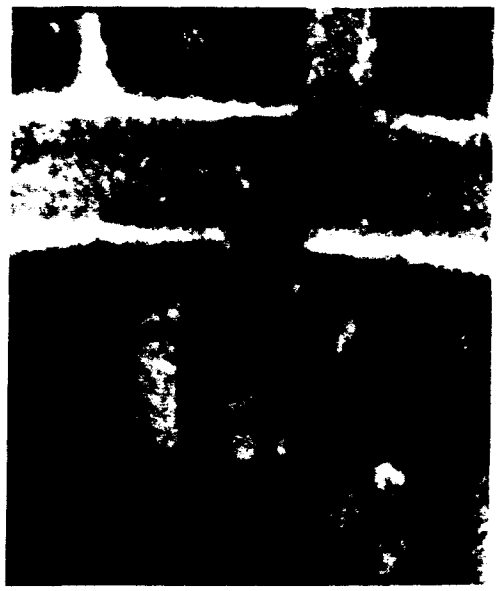


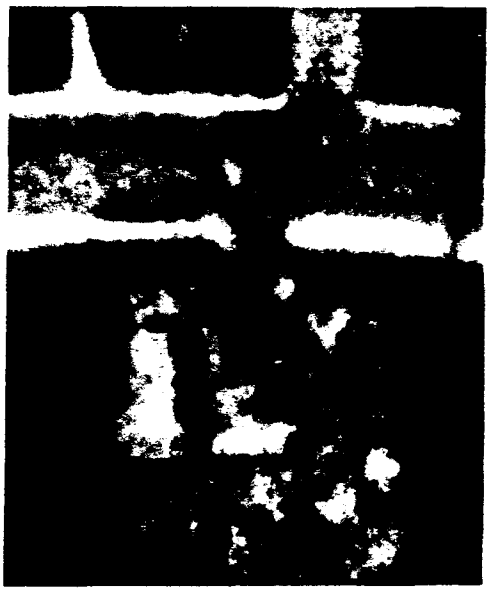
Fig. 3-1 — Print of 35-millimeter transparency showing selected area investigated

a. Kodachrome II

b. Kodak SO-121

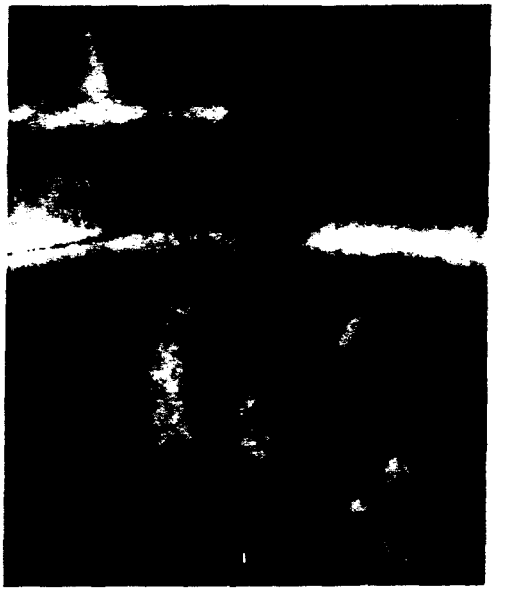


c. Ektachrome High Speed

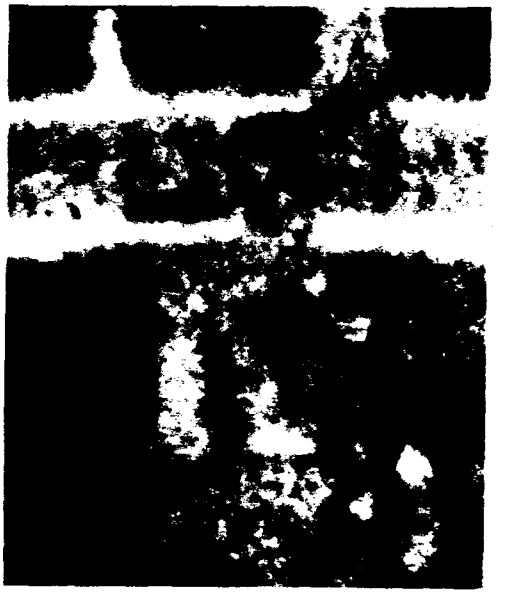


d. Ektachrome X

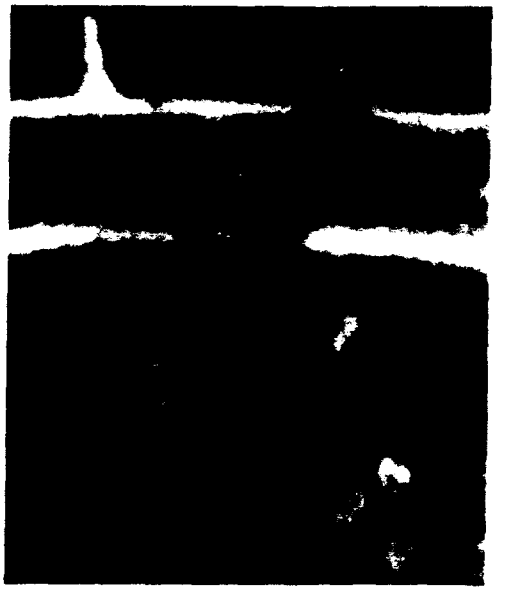
Fig. 3-2 — Small section of the model (90×)



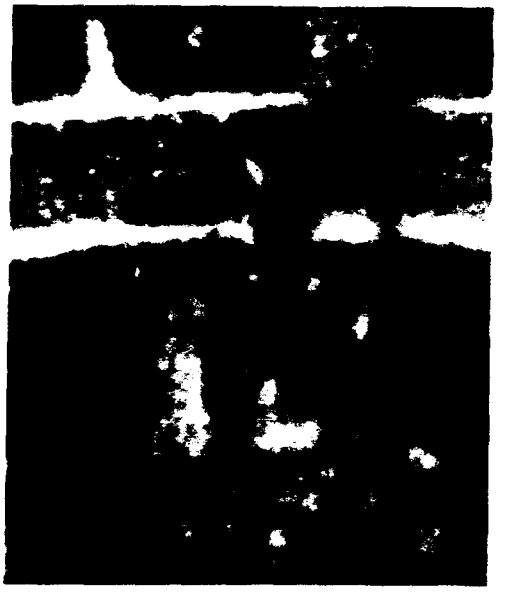
e. Anscochrome D/50



f. Anscochrome D/100



g. Agfachrome CT-13S



h. Agfachrome CT-18

Fig. 3-2 — Small section of the model (90×) (Cont.)

6. Anscochrome D/100 is very similar in its color characteristics to Anscochrome D/50. Saturation tends to fall off at the edge of objects due to poor edge characteristics.

Visual definition and edge sharpness are poor, the coarse grain structure that is objectionable at 10 diameters enlargement being the major factor.

The building under construction is unrecognizable as such and no detail shows in the parking lot lines.

Both samples of Anscochrome films are green overall to gross examination but exhibit good color and grey neutrals. Graininess is coarse and definition and visual acuity are poor and unable to withstand magnification of over 12 diameters.

7. Agfachrome CT-13S has an overall impression of green as did the Anscochrome samples. Color saturation is very good; highlights are well presented and bridge shadows are quite open with fair resolution of the detail contained.

Definition and visual acuity are very good with parking lot lines showing, but the house under construction falls short of showing joist detail.

Overexposure maintains good neutrals and good but desaturated colors. Graininess is about constant and definition and edge sharpness remain good.

Underexposure produces a dense but usable presentation with high color saturation, good neutrals, and an increase of graininess.

8. Agfachrome CT-18 produces a good color gamut tending slightly towards the red. Color saturation is good but falls off at the edge of image due to the poor edge acuity and coarse grain structure, both of which also adversely affect resolution.

Bridge shadows are closed and the house under construction is not recognizable without prior knowledge. It may be surmised, however, that construction is in progress, if the whole neighborhood is compared with this one spot.

Overexposure produces more objectionable grain and shifts the neutrals toward the red.

General Observations of Agfachrome Films

A blue veiling is present in dark areas around the model in the CT-13S that is neutrally black in the CT-18. A greenish overall color impression appears in the CT-13S that is not present in the CT-18; in fact, the green areas of the CT-18 are too neutral and deficient in green.

Grain is increased markedly in the CT-18 and sharpness is degraded as a result.

Comparison of Kodachrome II, Agfachrome CT-13S, and Kodak SO-121

The comparison of two films together was done with an A.O. split (ballistic type) microscope.

Kodachrome II Versus Agfachrome CT-13S

The two films compare quite well in regard to simulated CORN target resolution. However, the imagery of the model is superior on Kodachrome II, exhibiting superior edges, higher visual definition, and finer detail than the Agfachrome CT-13S, with added advantage of finer grain structure.

Color distinction is enhanced in the Kodachrome II by superior edges, also, contrasts between near hued colors is more apparent.

The overall comparison favors Kodachrome II over Agfachrome CT-13S for all of the above reasons plus an apparently high speed.

Comparison of Kodak SO-121 Versus Agfachrome CT-13S

Comparison of the simulated CORN resolution targets indicates that Agfachrome CT-13S has about 10 percent higher resolution than Kodak SO-121; not by a great margin, but noticeable on a point by point comparison basis. Grain is finer in the SO-121 sample, and though the frame appears to be deficient in green (more towards a neutral in fact) in vegetated areas, the distinction of other colors is more precise. This is particularly noticeable in closely matched colors.

The speed is higher in the SO-121 by a factor of 4× over that of the CT-13S.

Comparison of Kodak Kodachrome II and Kodak SO-121

Kodachrome II is distinctly superior to SO-121 in the context of this test series. It possesses a better color range and contrast, and the presence of green is a decidedly advantageous factor. Higher visual contrast, resolution, and visual acuity are present, and the equal speed of both films makes the Kodachrome II the obviously superior emulsion.

3.2 GENERAL CONCLUSIONS

Of the eight films subjected to analysis, three were considered for final comparative study: Kodak Kodachrome II, Kodak SO-121, and Agfachrome CT-13S.

The method of viewing the samples also has a bearing on information extraction capability as is demonstrated by the diverse performances of SO-121 under specular and diffuse illumination. It is recommended that viewing be done with diffuse illumination to minimize the peloid interference.

For future testing, it is recommended that comparisons of SO-121 and Kodachrome II be made for two reasons: (1) SO-121 is an "operational" film with a backlog of usage, and (2) Kodachrome II shows promise of being an emulsion that will increase the information content of color aerial photographs.

4. DISCUSSION

In view of the data presented in this document, Kodachrome II is recommended as the best color film from an image quality viewpoint. There are, though, several other considerations that should be taken into account before using this material in an operational mission.

The four basic characteristics of a color material to be considered are:

1. Image quality
2. Speed
3. Contrast, exposure latitude
4. Color rendition

Since Kodachrome II is faster than 3404, by about a stop, it has sufficient speed for use in mission photography. The contrast of the material is also comparable with that of 3404. The exposure latitude, though, is more restricted. An overexposure of one stop with this color material could be very harmful to the final image. With exposure errors using a black and white process, there are two safety factors available for correction. First, since a printing process is used, some of the information that was overexposed can be brought back. Secondly, the interrupted process used in the Trenton processor gives a wider exposure latitude. With the added exposure flexibility in the KH-4B System, though, this same type of flexibility is available for color materials.

Color rendition is the final consideration for a color material when used in a reconnaissance system. Although the spectral sensitivities, END curves, and the dye characteristics of the eight color materials varies somewhat, it is possible, through proper filtration, to obtain similar results with all of the films. An exact match, though, is not possible. However, it is not necessary for any one film (i.e., Kodachrome II) to match the results of another. All that is required is that a color image be formed that looks reasonably like the original scene.

A very important consideration to the use of Kodachrome II in an operational mission is that of film processing. There are no processing machines in existence today that will process 70-millimeter Kodachrome II film. The manufacturer can produce the film in 70-millimeter widths, though currently the only way to process it would be to slit it into two 35-millimeter widths and use one of Eastman Kodak's standard Kodachrome processors. This approach has been used for test purposes in the mission 1036 low gamma experiment. By splitting the film before processing, only a very small portion is lost in the center. It is recommended that this type of processing be done with any mission test of Kodachrome II.

At present, Kodachrome II film has a base which is too thick to run through the camera. If mission tests are to be performed, this emulsion will have to be coated onto a thinner film base.

Appendix

A BRIEF SUMMARY OF COLOR DENSITOMETRY

In comparison to the standard black and white densitometry which we are all familiar with, color densitometry is a relatively complicated field of endeavor. The prime reasons for the complications are: (1) the fact that color as well as brightness differences are now involved, and (2) the fact that the components of the image are three colored dyes arrayed in individual layers. Because of the inherent complexity of the evaluation of such imagery, many different densitometric techniques for the evaluation of color images have been generated, each with a specific purpose. These notes have the prime purpose of discussing some of these densitometric techniques as applied to the evaluation of images on color film.

1. INTEGRAL DENSITIES

There are basically two types of color densitometry—integral and analytical. Integral densities describe some action of the color image as a whole, and they do not directly yield information about the amounts of the individual colorants of which the image is composed. There are five different types of integral densities.

1.1 Integral Printing Densities

Density measurements are made in a densitometer whose response matches a given printing material.

1.2 Colorimetric Densities

These densities are measured with a filtered photocell to match the standard ICI colorimetric responses of a standard observer.

1.3 Luminous Densities

Luminous density is the apparent density of a colored object in respect to the standard ICI observer. This density does not take into account the color of the material. It may be measured electrically or visually.

1.4 Arbitrary Three Filter Densities

These densities are measured in a densitometer with three arbitrary red, green, and blue wide bandpass filters. They do not correspond to any specific film usage. These densities are primarily useful in quality control where the only information of interest is to determine if today's run is the same as yesterday's.

1.5 Integral Spectral Densities

These densities are a fundamental measurement of the film. They are measured in a densitometer to very narrow bandpass filters, preferably monochromatic light.

2. ANALYTICAL DENSITIES

Integral densities always describe some action of the color image as a whole. They do not directly yield information about the image composition in terms of the individual amounts of dye. A subtractive color process image is thought of as composed of cyan, magenta, and yellow dye, and with certain reservations, this is correct. The cyan dye primarily absorbs red light, the magenta dye primarily absorbs green light, and the yellow dye primarily absorbs blue light. To a smaller extent, however, the cyan dye absorbs also green and blue light, the magenta dye absorbs red and blue light, and the yellow dye absorbs green and red light. These absorptions are known as the "unwanted" absorptions of the various dye layers. Integral density measurements show the total effect of all these absorptions. Analytical density measurements determine the individual amounts of each of the three dye deposits. The amounts of dye deposits determined then can be expressed in any of several useful density units.

2.1 Spectral Analytical Density

The amount of each dye is expressed as a function of wavelength.

2.2 Equivalent Neutral Density

The amount of the dye is expressed as the luminous density of the gray image that would be formed by adding to the single dye deposit sufficient quantities of the other dyes of the color process to form a neutral.

2.3 Equivalent Neutral Printing Densities

Same as the above except adding sufficient amounts of the various dyes to obtain an image with the R, G, and B printing densities equal.

3. SPECTRAL ANALYTICAL DENSITIES

Various analytical densities differ from each other in the type of measure in which the amounts of each of the dyes are expressed. One of the simplest types of measure is the spectral analytical density, or the density of the dye at some particular wavelength. The amount of cyan dye, for example, in a given piece of film may be expressed in terms of the density which this dye has at, say 650 millimicrons. Usually the wavelengths chosen for routine analysis of the spectral analytical densities of emulsions correspond to the peak wavelength of dye absorption. The basic calibration of the dye layers in a color film is a plot of the spectral analytical density versus wavelength.

4. EQUIVALENT NEUTRAL DENSITIES

Probably the most useful of the analytical densities is the equivalent neutral density. This density is defined as the visual density the photographic image should have if it were converted to a neutral gray by superimposing the just required amounts of the fundamental colors of the process.

The relationship between equivalent neutral densities and the spectral density of a selected set of dyes is illustrated in Fig. A-1. The curves C, M, and Y show the spectral analytical densities of the cyan, magenta, and yellow dyes which together form the neutral shown by curve N. For the example, the luminous density of the curve N is 1.0. In accordance with the definition of END, each of the component dye layers also has an END of 1.0 regardless of the absolute value of spectral analytical density for that dye layer.

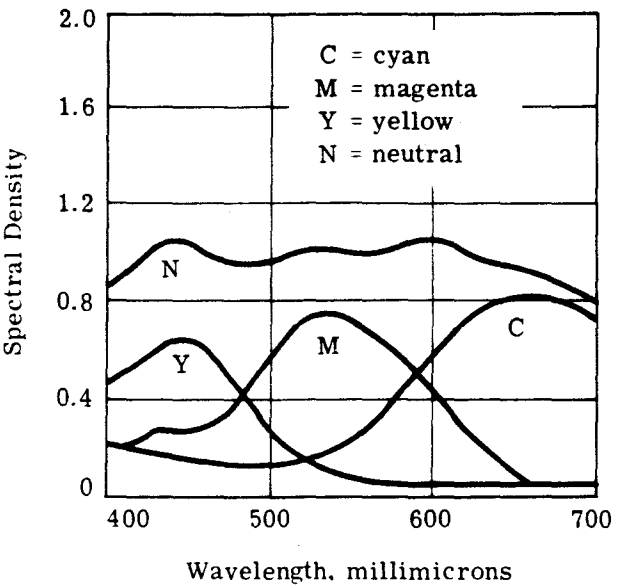
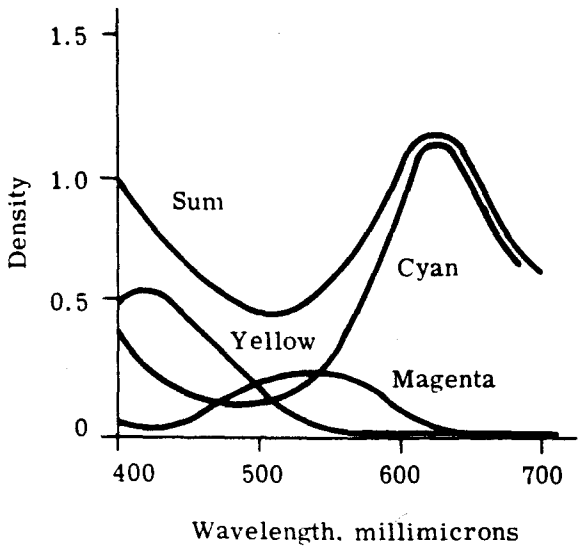


Fig. A-1 — Spectral density of a selected set of dyes

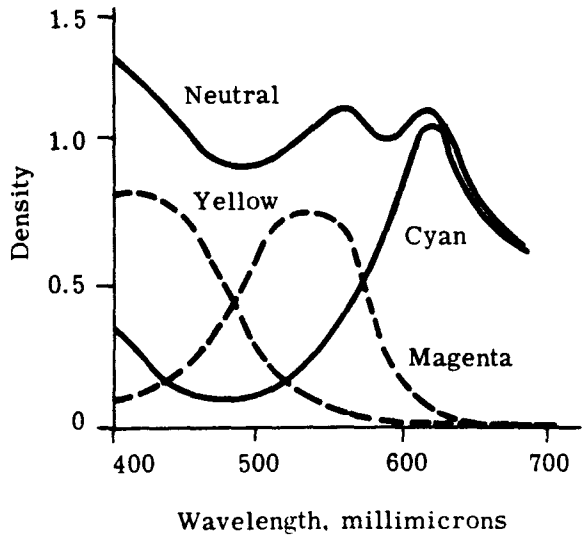
A combination of different amounts of these dyes is shown in Fig. A-2 (a, b, c, d). As is evident from the new concentrations [Fig. A-2(a)] this sample is not neutral. In Fig. A-2(b), the cyan dye is shown by the solid curve and sufficient amounts of magenta and yellow dyes to make a neutral are shown by the dashed curves. The density of this neutral is 1.0. The END of the cyan component of the Fig. A-2(a) example is therefore 1.0.

Fig. A-2(c) shows the magenta dye for Fig. A-2(a) and the corresponding amounts of cyan and yellow dyes necessary to give a neutral. The luminous density of this neutral is 0.3. The END of the magenta layer shown in Fig. A-2(a) is therefore 0.3.

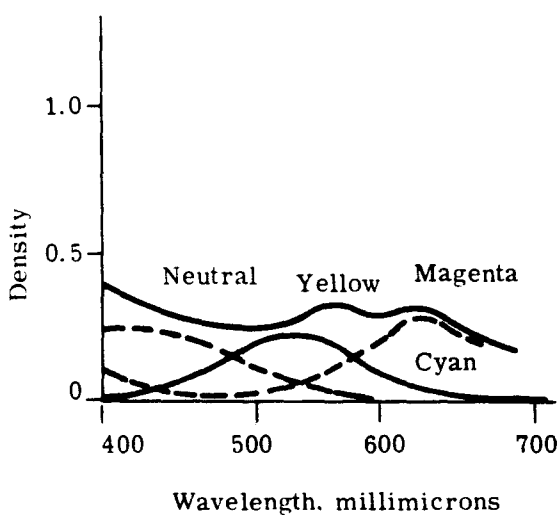
Similar combinations to give a neutral for the yellow dye are shown in Fig. A-2(d). The luminous density of this neutral, and consequently the END of the yellow dye in Fig. A-2(d) is 0.6.



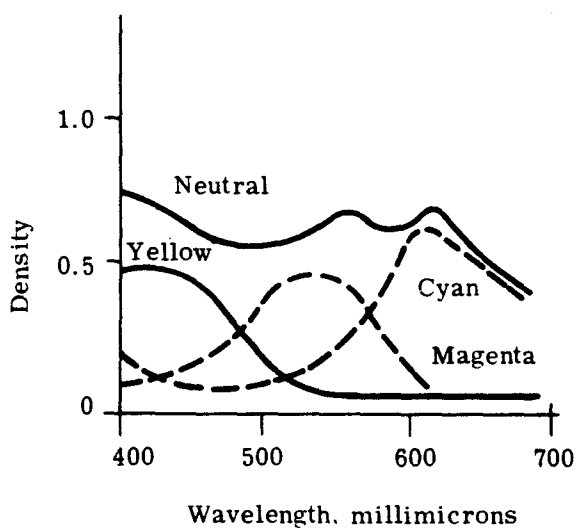
a. Not neutral density



b. Neutral density = 1.0



c. Neutral density = 0.3



d. Neutral density = 0.6

Fig. A-2 — Combinations of different amounts of dyes

5. INTEGRAL DENSITIES AS A FUNCTION OF DYE SPECTRAL ANALYTICAL DENSITY

Assuming that for many applications the END's of a particular image are of most benefit, the question becomes how to determine such densities. It has already been shown that END's can be determined knowing the spectral analytical densities of the dye layers composing a particular image on the film. The problem is that spectral analytical densities are impossible to measure directly on a piece of color film after an image has been exposed and developed for the intended use. The type of measurements that can be made, however, are integral spectral densities. A later section will illustrate how one can determine the spectral analytical densities from the integral analytical densities, and then how the equivalent neutral density (END) can be determined from the integral spectral density. It is sufficient to point out at this time that these conversions are possible solely because photographic dyes used in color films obey within reason the log-D law, that is, as the concentration of a dye changes, its density changes linearly. For example, if the concentration of a dye in the color film is doubled, its density is also doubled.

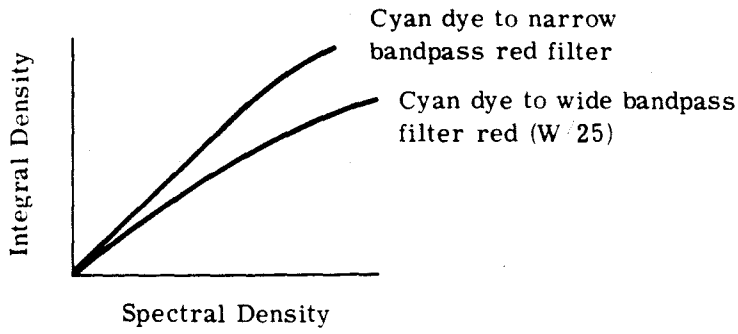


Fig. A-3 — Relationships between the spectral analytical density of a cyan patch and the integral spectral density

It is extremely important to understand first, however, that integral densities (spectral or otherwise) are not strictly valid when measured with wide bandpass filters, due to the nonlinear density response when compared with pure spectral (monochromatic) light densities. For example, Fig. A-3 illustrates the relationships between the spectral analytical density of a cyan patch and the integral spectral density when the integral density is measured with filters of differing bandwidth. As indicated in Fig. A-1, the integral spectral density of a color film at a given wavelength is simply the sum of the spectral analytical densities at that wavelength. This additivity of spectral densities does not hold, however, for wide bandpass filters but only for very narrow bandpass filters. For example Fig. A-4 illustrates the spectral density distributions of three different red filters, each of which was used to measure the densities on a series of patches on a cyan strip and a magenta strip, and then to measure the densities of the same patches with the two strips superimposed.

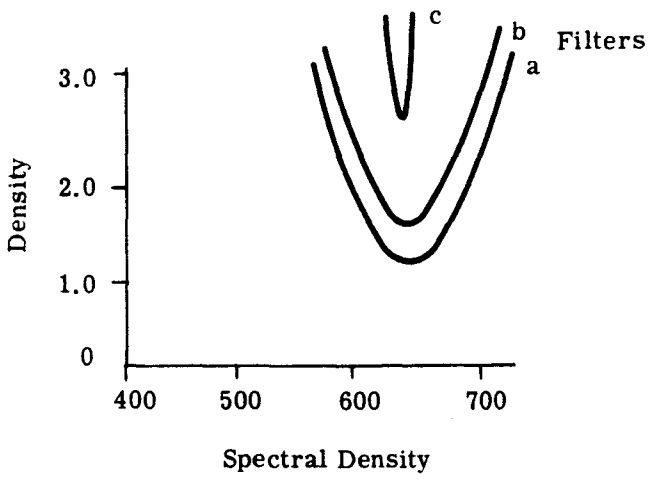


Fig. A-4 — Spectral density distributions of three different red filters

The next series of figures (Fig. A-5) compares the sum of the individually measured densities against the deviation from these densities as measured when the strips were superimposed. Only filter c (the narrow bandpass filter) approaches the ideal of no deviation between predicted (or sum) and actually measured integral spectral density.

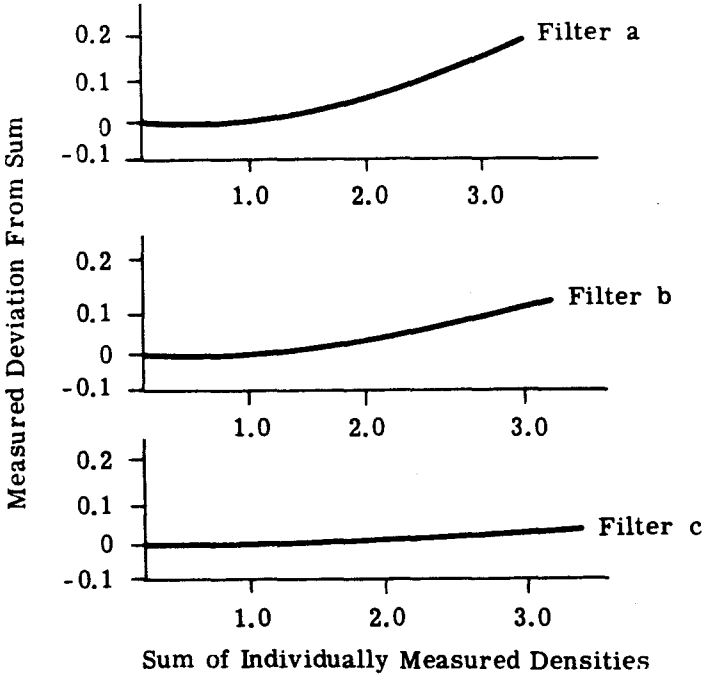


Fig. A-5 — Sum of individually measured densities versus the deviation from these densities when the strips were superimposed

If the new values of D_r, D_g, and D_b are measured or known, and the coefficients B_m, G_y, etc., are also known (from the previous table) then the above equation can be solved for c', m', and y' by matrix algebra. As an example, using the previous dye set and substituting in the above equations we obtain:

$$D_r = c' + 0.059m' + 0.013y'$$

$$D_g = 0.220c' + m' + 0.048y'$$

$$D_b = 0.254c' + 0.154m' + y'$$

Solving the above equations by matrix algebra allows the determination for any new set of integral spectral densities of the amount of each individual color former (i.e., the spectral analytical densities), the above equations become:

$$c' = 1.015D_r - 0.058D_g - 0.010D_b$$

$$m' = -0.213D_r + 1.019D_g - 0.046D_b$$

$$y' = -0.225D_r - 0.142D_g + 1.010D_b$$

The determination of the equivalent neutral densities (END) from the integral spectral densities is equally straightforward. A sample of the color film is exposed to produce a neutral.* The integral spectral densities of this neutral are determined, and using the above equations, the spectral analytical densities are calculated. By definition the END of each of the dye layers forming the neutral is equal to the luminous density of the neutral, regardless of the spectral analytical density of the dye layers. As an example consider a sample exposed to produce a neutral image with a luminous density of 1.0. The END of the cyan, magenta, and yellow layers is by definition 1.0. Even though the spectral analytical densities in all probability will be different, say for this example:

$$c' = 1.052$$

$$m' = 0.751$$

$$y' = 0.826$$

6. RELATIONSHIPS BETWEEN INTEGRAL AND ANALYTICAL DENSITIES

As has already been mentioned, the images in a color film are a result of the separate actions of the three dyes, and the integral and analytical densities are both a measurement of this action by the dyes. Because of the fact that both measurements (i.e., integral and analytical) are a

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* The exposure of a piece of color film to produce a neutral is not always simple. However, by definition for the purposes of determining the END's of color dye layers, a neutral exposure is commonly accepted as the exposure of the color film to a neutral wedge (such as type 3 carbon) with the colorant of illumination the film is intended to be used with (such as daylight, tungsten, flash, etc.)

measure of the action of the dyes, and since the dyes follow the log-D law, it follows that there is a correlation between the two types of density measurement.

Curve s of Fig. A-6 represents the integral spectral densities of an image consisting of three dyes. An increase or decrease in the amount on any one of the dyes in this image would result in a corresponding increase or decrease in density at all wavelengths. The combined density of the three dyes at any one wavelength does not, therefore, indicate the extent to which any one of the dyes contributes to this density, unless the spectral absorption characteristics of the dyes are known. If these characteristics are known, the extent to which each dye contributes to the integral spectral density measurement can be determined.

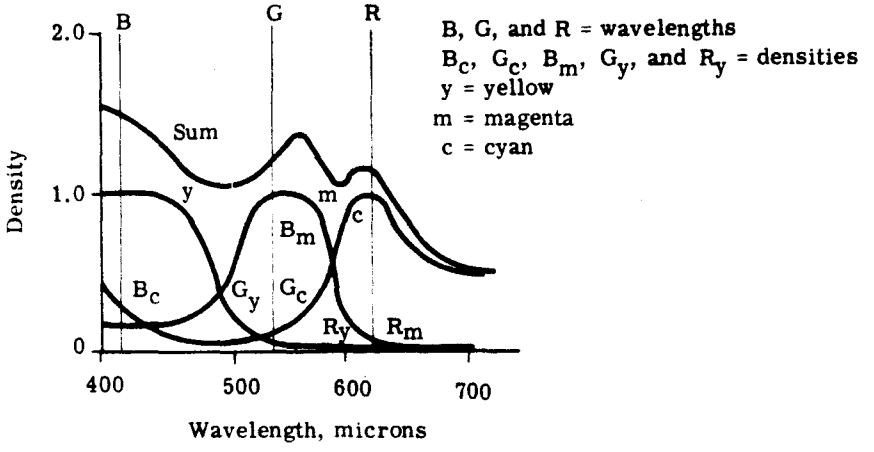

Fig. A-6 — Integral spectral densities of an image consisting of three dyes

The amounts of the dyes will be specified in terms of the spectral analytical densities c′, m′, and y′. By definition, a unit concentration of dye is when the spectral analytical density is 1.00 at the peak absorption of the dye. The wavelengths are labeled R, G, and B for the cyan, magenta, and yellow dyes respectively. Besides the amount of the primary dye absorption at a given wavelength, the amount of "unwanted" absorptions from the other dyes must also be known. There are six such densities and they are designated as G_c, B_c, B_m, R_m, G_y, and R_y. These densities are noted in Fig. A-6, and their numerical values for the particular dyes illustrated in Fig. A-6 are tabulated below. The letters R, G, and B are used to denote the color of the measuring light. The letters c, m, and y are used to denote the dye layer being measured. On this basis it is evident that R_c, G_m, B_y = 1.00.

Spectral Analytical Densities

Density, millimicrons	(c) Cyan Dye	(m) Magenta Dye	(y) Yellow Dye
(R) 620	1.000	0.059	0.013
(G) 540	0.220	1.000	0.048
(B) 410	0.254	0.154	1.0000

Let us now consider these dyes in amounts which differ from those given in Fig. A-6. For any given amount of cyan dye c′, the density of this dye to red light would be c′, to blue light $B_c c'$, and to green light $G_c c'$. The same relationships hold for the other dyes. The integral spectral densities D_r, D_g, and D_b, to red, green, and blue light respectively, of any combination of these dyes, is simply the sum of the spectral analytical densities contributed by each dye component as shown in the following equations:

$$D_r = c' + R_m m' + R_y y'$$
$$D_g = G_c c' + m' + G_y y'$$
$$D_b = B_c c' + B_m m' + y'$$

The END of each layer (c, m, y) is thus related to the analytical spectral density by the equations:

$$\text{END's} \begin{cases} c = \left(\frac{1}{1.052}\right) c' = 0.951c' \\ m = \left(\frac{1}{0.751}\right) m' = 1.332m' \\ y = \left(\frac{1}{0.826}\right) y' = 1.211y' \end{cases}$$

By combining the above relationships between END and ASD with the equations for the determination of analytical spectral density (ASD) from integral spectral density, one can solve directly for the END of a dye layer from the integral spectral density. Thus:

$$c' = 1.015D_r - 0.058D_g - 0.010D_b$$
$$m' = 0.213D_r + 1.019D_g - 0.046D_b$$
$$y' = 0.225D_r - 0.142D_g + 1.010D_b$$

From the END equations above:

$$c' = \frac{c}{0.951}$$
$$m' = \frac{m}{1.322}$$
$$y' = \frac{y}{1.211}$$

Substituting c/0.951, m/1.332, and y/1.211 for c′, m′, and y′ respectively, we obtain:

$$\text{END's} \begin{cases} c = 0.965D_r - 0.055D_g - 0.010D_b \\ m = -0.284D_r + 1.357D_g - 0.061D_b \\ y = -0.272D_r - 0.172D_g + 1.223D_b \end{cases}$$

Thus, to obtain the END's of any combination of the above set of color formers, it is only required to measure the integral spectral density. Once the above equations are established there is no need to recompute them for the same color film, as long as the type of dye used remains the same.

7. REFERENCES

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