Joseph H. Altman. "Densitometry Measurement."

Densitometry Measurement

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57.1 Introduction

As the name indicates, densitometry is the measurement of optical density (O.D.). Optical density, in turn, can be broadly defined as a measure of the attenuation of radiant flux by some sort of optical element that can be transmitting, reflecting, or both. Densitometry is most widely applied in photographic science, and measurements in this field are covered by a four-part ANSI/ISO standard [1]. The treatment here follows that document. The measurement of transmission and reflection from the standpoint of optics has been discussed by Palmer [2]. This chapter uses the single word density, without the adjective, and uses the words "light" and "flux" interchangeably (although density can be measured in the UV and IR also, of course).

It turns out that, in practice, the measured density of a given sample can be affected significantly both by the design of the equipment and the nature of the sample. Therefore, the first rule of practical densitometry is that the sample must be measured in a way that is meaningful with respect to its intended use.

57.2 Monochrome Transmission Density

It is convenient to start by discussing transmitting samples, without the color aspect. Such samples can be either black-and-white photographic films or filter layers of various sorts. If light falls on such an element, a fraction of the flux is reflected from the first surface. The remainder penetrates the surface, and a part of this flux is absorbed. What is neither reflected nor absorbed exits the layer, as shown in Figure 57.1. Let these fractions be denoted, r, a, and t, where lower-case t indicates internal transmittance. If the element is in air, reflection can occur at the rear surface also, but this can be neglected. By the conservation of energy, one obtains
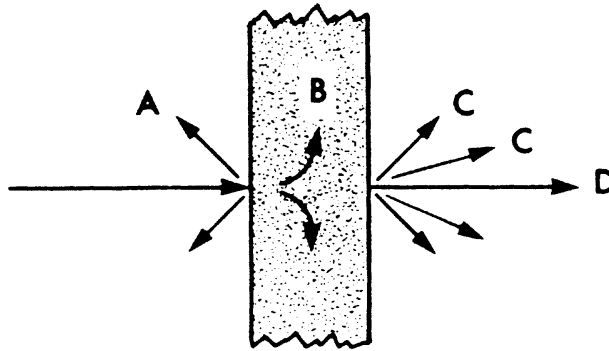
$$r + a + t = 1 \tag{57.1}$$

FIGURE 57.1 Cross-section of emulsion layer showing (A) reflection, (B) absorption, (C), diffuse transmission, and (D) specular transmission.

The fractions *r* and *t* can be measured independently by spectrophotographic techniques, so that *a* is readily determined. This fraction is termed the absorptance of the layer, and its measurement is also discussed by Palmer [2].

Some applications require the measurement of absorptance, but in most practical work, what is important is the fraction of the incident light that exits the element, regardless of where attenuation takes place. Therefore, transmittance is defined by:

$$T = \frac{\Phi_e}{\Phi_i} \qquad (57.2)$$

where e and i refer to emergent and incident flux, respectively. Note that all losses are lumped together. In silver halide photographic layers, the first-surface reflection is usually small; in thin-film filters, a significant proportion of the total loss may occur by reflection. Following Hurter and Driffield [3], the English pioneers of densitometry, one can define the transmission density *D*

$$D = -\log_{10}T = \log_{10}\frac{1}{T} \qquad (57.3)$$

Density is therefore a nonlinear dimensionless quantity ≥ 0. McCamy has published an extensive review of densitometry and sensitometry [4].

The operation of a practical densitometer can be discussed with reference to Figure 57.2. The system consists of a light source, an aperture to define the area being measured, a sensor, logging circuitry, and a suitable readout display. In many instruments, the output is fed to a computer.
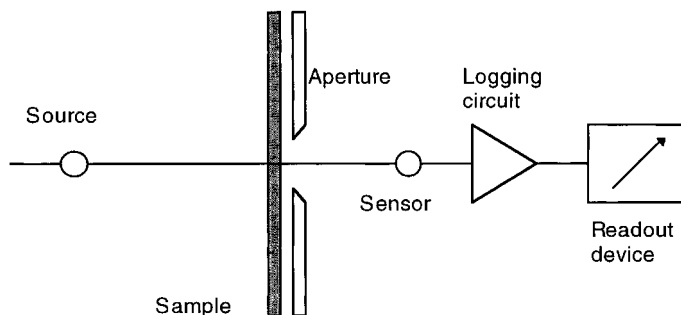

FIGURE 57.2 Schematic of transmission densitometer.

To measure transmittance/density, a reading is first taken with no sample over the aperture. This reading is a measure of the incoming light Φ_i. A second reading with the sample in place then determines Φ_e. It should be clearly understood that what the system actually does is to sense the flux passing through the aperture in the two cases, and then displays the negative logarithm of the ratio. This fact explains some of its operating characteristics. Starting from this basis, for example, McCamy [5] has treated measurement errors for the case when the sample is not uniform ("wedged") over the aperture.

The basic procedure also means that any source having enough power to operate the sensor can be used, and filters and apertures can readily be interchanged; it is only necessary to "zero" the instrument before making a measurement. The measuring aperture is usually of the order of 1 mm in diameter. If the area of this aperture is reduced to, say, 0.1 mm², the device becomes a microdensitometer. Such instruments present special problems not discussed here but treated in the literature [6].

Now consider the complications introduced by the nature of samples, especially photographic samples. Developed black-and-white photographic layers consist of discrete grains of silver metal dispersed in a thin layer of gelatin. Such grains act as scatterers, which means that some of the photons exiting the layer will not be traveling in their original directions. Such photons are identified by "C" in Figure 57.1. Clearly, the measured transmittance/density will depend on how much of this scattered light reaches the sensor. The effect of scattering can be quite large, and therefore in order to obtain values that are both reproducible and meaningful it is necessary to control what is termed the "geometry" of the system, i.e., the angular subtenses of the influx and efflux beams at the sample.

In Figure 57.3, Θ_i and Θ_e are these half-angles, respectively, referred to the normal to the element surface. The current standard [1b] prescribes two configurations, the first of which is as follows: $\Theta_i = 5°$; $\Theta_e = 90°$. The reverse of this configuration, i.e. $\Theta_i = 90°$; $\Theta_e \leq 5°$, yields the same density readings and is also permitted by the standard. This case is termed "diffuse density" and is the most important practical case because most commercial densitometers conform to this mode. Essentially, all the light exiting the sample, whatever its direction, reaches the sensor and is evaluated. This configuration simulates the case of contact printing a photographic negative, or of viewing a transparency on a diffuse illuminator. The practical construction of such an instrument is described below.

The second case occurs when the sample is illuminated, and the emergent flux collected, by lenses of finite aperture. In principle, in this case, the angles Θ_i and Θ_e can vary between, say, 5° and 90° and may differ from one another, but the standard specifies two sets of optics with matched apertures of $f/1.6$ and $f/4.5$. These relative apertures are representative of motion picture projectors and microfilm readers, respectively. The corresponding half-angles are 18.2° and 6.4°. (For a lens in air, $f/no. = 1/(2\sin\Theta)$, where Θ is the half-angle shown in Figure 57.3.) This case is termed "projection" density.

It is useful to define a ratio

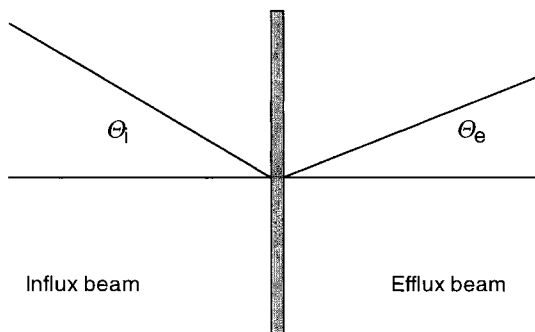$$Q' = \text{Projection density/diffuse density} \tag{57.4}$$

FIGURE 57.3 Angular subtenses of influx and efflux beams at sample.

which has been termed the "effective Callier coefficient." As would be expected, projection density is greater than diffuse density for a given sample so that $Q´ = 1$. The exact ratio between the two densities depends on the scattering characteristics of the sample and the *f*-numbers involved. Only limited information on $Q´$ has appeared in the literature [7] but, as Figure 57.4 shows, this parameter behaves as might be expected.

The dependence of the effective density on aperture shown in Figure 57.4 may be important in practice. Amateur photographers are aware that a B&W negative usually produces a more contrasty print in a condenser enlarger than it does in a diffuser enlarger, and this behavior can easily be deduced from Eq. (57.4). It may also be important in microdensitometry, since these instruments measure a projection density and a wide range of apertures may be encountered in various instruments. In such cases it is usually recommended that the data be reduced to diffuse density. This is easily done by measuring a sufficiently large sample in both projection and diffuse densitometers. It might be remarked that the scattering characteristics of individual films can vary significantly, and $Q´$ should be measured for the samples at hand. Except for very low densities, $Q´$ is relatively unchanged as the diffuse density varies.

For completeness, it is noted that earlier editions of density standards listed two other forms of density. The first of these was the case of angle Θ_i = angle $\Theta_e \leq 5°$. This case was termed "specular density" and was intended to simulate the use of the attenuating element in a collimated beam. The second case was the case of angle Θ_i = angle Θ_e = 90°. This type of density was termed "doubly diffuse," and was intended to simulate the use of a negative in certain contact printers. Neither of these densities is important in modern practice; discussions of them can be found in the literature. [8].

In a color film, the "grains" are actually tiny volumes of dyed gelatin. Since the index of refraction of such a "grain" is only slightly different from the surround, it does not act as a scatterer. Thus, the density differences found on color films as a function of densitometer geometry are usually negligible and often ignored in practice.

In recent years, the photographic industry has introduced a new type of grain, the "tabular" grain, whose thickness is much smaller than the dimensions in the plane parallel to the coating surface. It has been demonstrated that, in the undeveloped state, these grains scatter light significantly less than the older "3-D" types of grains. No studies of developed T-grains have appeared in the literature, but it seems possible that developed B&W layers consisting of T-grains may scatter less than the traditional types of layers, thus reducing the sensitivity of density measurement to instrument geometry. (The data of Figure 57.4 were obtained with "3-D" grains.)

One can now turn to the optical configuration of a practical diffuse densitometer. From an optical standpoint, a good way to collect all the flux exiting the sample would be to use an integrating sphere,
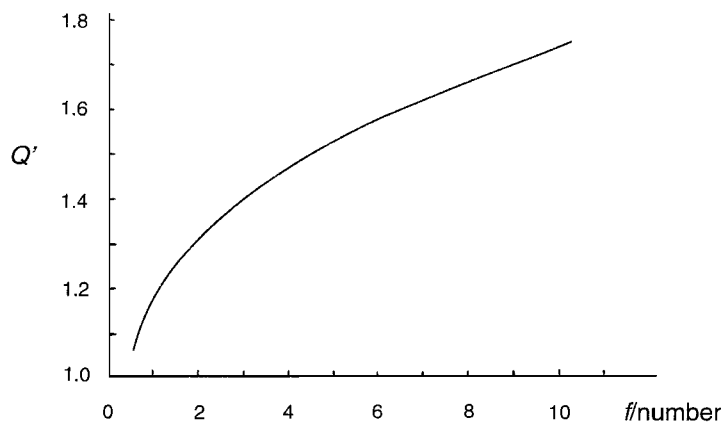

FIGURE 57.4 Variation of the effective Callier $Q´$-factor with the *f*-numbers of the influx and efflux beams, which were matched.

and instruments have been built using such spheres. However, in an actual contact-printing case there will be some light reflected back to the negative from the paper surface. Any retroreflection from an integrating sphere will of course be quite different from that coming from a paper surface. The better to simulate the contact-printing case, the present ANSI/ISO standard specifies that, in diffuse densitometers, the emulsion side of the sample shall be in contact with opal glass, which both acts as the diffuser and provides the desired back reflection. The optics of a diffuse densitometer are shown in Figure 57.5.

In the system shown, the sample is illuminated by diffuse light, which is the reverse of what is shown in Figure 57.3; however, as noted, diffuse density optics are reversible. Weaver studied the differences between opal-glass and integrating-sphere densities and found that because of the interreflections, the values were slightly lower in the opal-glass case [9]. The difference was ~0.04 density unit for very low densities, decreasing to 0.01 to 0.02 for samples whose densities were between 2.0 and 3.0. The opal-glass construction was also adopted in the standard because such instruments are easier to build and maintain. Care must be taken, however, to ensure that the diffuser meets the standard's specifications.

In actual operations, it is too time-consuming to zero the instrument before each reading. Likewise, the fraction Φ_e/Φ_i is rarely calculated specifically; the instrument simply provides a reading based on the amount of flux reaching the sensor. Because of the possibility of electronic drift however, it is advisable to zero the instrument periodically, unless it is known to be dependably stable. Likewise, the readings produced for some accurately known calibration sample of high density should be checked, a procedure known as "sloping" the instrument. Standard samples are available for this purpose; see the Appendix.

57.3 Monochrome Reflection Density

By definition, the reflectance factor

$$R \;=\; \frac{\Phi_r}{\Phi_o} \tag{57.5}$$

where Φ_r is the flux returned to the sensor from the sample, and Φ_o is the flux returned by a "perfectly reflecting, perfectly diffusing material located in place of the specimen" [1d]. Reflection density is then

$$D_R \;=\; -\log_{10}R \;=\; \log_{10}\frac{1}{R} \tag{57.6}$$

The optical configuration specified in the standard is shown in Figure 57.6. With reference to the normal to the specimen surface, one beam subtends an angle of $0 \pm 5°$ and the other an angle of $45° \pm 5°$. Also, the 45° beam is annular. As in the case of transmission optics, the influx and efflux beams are interchangeable. When the influx beam is at 45°, the system is termed "45/0"; when the efflux beam is at 45°, the designation is "0/45." The angle between the two beams was selected to avoid the specular reflection from the surface. The 45° beam is made annular to minimize the effects of any texture pattern that might be embossed on the sample surface. The standard also specifies that when measured, samples
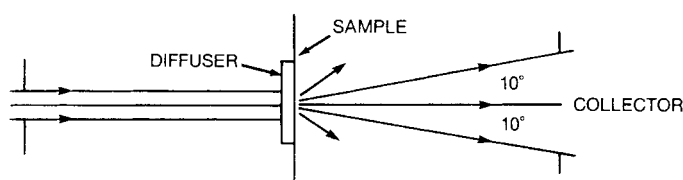

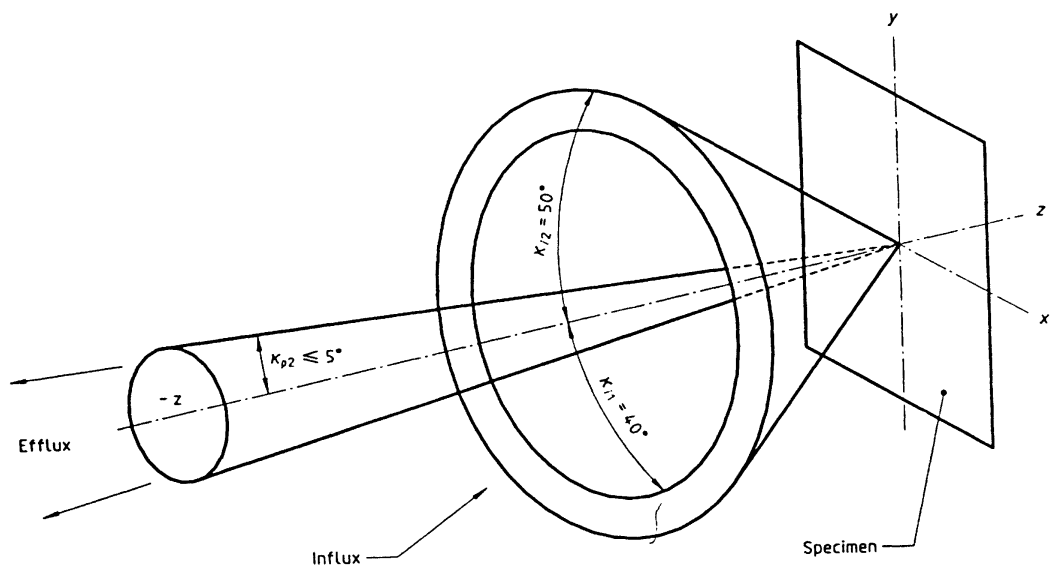**FIGURE 57.5** Optical system for measuring ISO diffuse density.

FIGURE 57.6 Annular geometry for measurement of reflection density.

shall be backed by a black diffusing material having a reflection density not less than 1.5. This procedure is specified to improve reproducibility, especially for thin samples.

It will be obvious that a reflection densitometer cannot be "zeroed" by taking a reading with no sample in place. Instead, as prescribed by the Standard [1d], calibration samples that have been measured on other primary instruments are used both to zero and slope the densitometer. Formerly, coatings of MgO_2 or $BaSO_4$ were used as reference "whites," but these layers are difficult to use. An ASTM standard [10] discusses the preparation of reference whites from pressed powders. For routine work, "plaques" consisting of stove enamel of various gray levels on a metal substrate are widely used. These plaques are very durable, but their physical form is quite different from actual paper samples. Photographic paper strips that have been calibrated in primary instruments can also be used. Physically, these strips are exactly like the samples to be read, but they are very easily damaged and must be used with care. Any scratch in the surface can cause a specular reflection to reach the sensor, which will produce a false reading.

Actually, the reflection of light from a photographic paper is more complicated than might appear at first glance. A typical B&W paper is shown in cross section in Figure 57.7. As with film samples, the emulsion layer consists of Ag grains suspended in gelatin. The support is a diffuse reflector. It turns out that reflection to the sensor occurs in three ways, as sketched. (The specular reflection is omitted in Figure 57.7.) Note that the component r_2 traverses the emulsion layer twice and r_3 at least four times, and that r_1 does not traverse the layer. For low densities, all three components contribute to the reflection reading. As the population of grains in the emulsion layer grows, the multiply-reflected beam r_3 rapidly becomes negligible. With continued increases in the grain population, the component r_2 also reduces to insignificance, and only the r_1 component remains. This component, being a surface reflection, remains essentially constant at about $0.005I_0$.

The mechanism described above can be confirmed by measuring the densities of a test strip by transmission and then cementing the strip to a diffuse reflector and measuring the same densities by reflection. The results of such an experiment are shown in Figure 57.8. This curve has three regions, as expected. In the first region, the slope is greater than 2, corresponding to the rapid loss of the r_3 component. In region 2, $\Delta D_R = 2\Delta D_T$; in this region, most of the photons reaching the sensor are those that have traversed the layer twice. Finally, in the third region of the curve, the r_2 component has become negligible, and only the surface component r_1 remains significant. Since, as noted, this component $\sim 0.005I_0$, the maximum reflection density attainable in a photographic paper should be about 2.0 to 2.3,
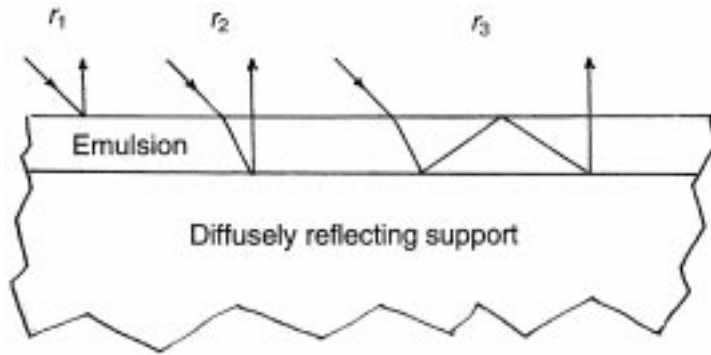
FIGURE 57.7 Cross-section of photographic paper showing different reflection paths for influx beam: r_1, surface reflection; r_2, direct reflection from support to sensor; and r_3, one or more internal reflections before reaching sensor.

and this is found to be the case for actual papers. (We have assumed a glossy paper. If the paper surface is textured, as it is in some products, specular reflections may be directed to the sensor from microareas and the maximum density attainable on the sample will drop, in some cases significantly.) The curve of Figure 57.8 also becomes very important in color reflection work, as is discussed below.

57.4 Color Transmission Densitometry

So far, we have assumed either that the measuring beam was monochromatic or that the sample was neutral, i.e., that transmittance or reflectance was constant across the spectrum of interest. Actually, the assumption of neutrality is reasonable for many B&W materials. However, of course, the densitometry of color images is extremely important, and this aspect is discussed below.
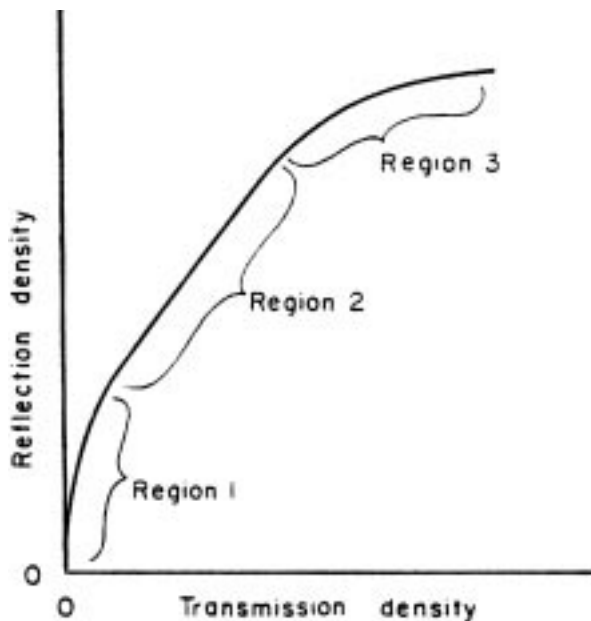

FIGURE 57.8 Densities measured on a film sample, both by transmission and after cementing the emulsion side to a diffusing reflector.

Before doing so, however, it will be useful to make a brief digression into the structure of photographic color materials [11]. Although an oversimplification, we can consider such materials to be three separate films coated one over the other on a single support. From the top down, the spectral sensitivities of these three layers are adjusted to record the blue, green, and red regions of the visible spectrum, respectively. In accordance with the principles of subtractive color reproduction, the images recorded in these layers are formed of yellow, magenta, and cyan dyes (again from the top down). The problem is to densitometer these dyes. As before, we start with transmitting samples. Referring back to Figure 57.2, for any wavelength λ, the reading of the instrument with no sample in place will be

$$KS_\lambda s_\lambda F_\lambda = KJ_\lambda \tag{57.7}$$

where K = proportionality constant, S_λ = spectral power of the influx beam at λ, s_λ = relative spectral sensitivity of the receiver at λ, and F_λ = transmittance of any filters in the beam at λ. (The transmission of the instrument optics may be significant, but this can be included with S_λ, since it is a fixed characteristic of the device.) The product J is termed the "response" or the "spectral product" of the instrument.

If a sample whose transmission at wavelength λ is T_λ is now placed over the aperture, the reading will be

$$KS_\lambda s_\lambda F_\lambda T_\lambda = KJ_\lambda T_\lambda \tag{57.8}$$

and the measured transmittance reduces to T_λ, as it should. Thus, in the monochromatic case, the measured value is independent of the system response. When the influx beam contains two discrete wavelengths, the no-sample reading becomes

$$K(J_1 + J_2) \tag{57.9}$$

and with the sample in place it will be

$$K(J_1 T_1 + J_2 T_2) \tag{57.10}$$

The measured transmittance

$$T = \frac{J_1 T_1 + J_2 T_2}{J_1 + J_2} \tag{57.11}$$

Note that when the sample is neutral, Equation 57.11 again reduces to the case where the transmittance is independent of the instrument response. But when the sample is not neutral, Equation 57.11 can no longer be simplified. In other words, in the general case the transmittance/density values depend on the system response as well as on the sample.

For continuous bands of radiation, Eq.(9) becomes

$$T = \frac{\int J_\lambda T_\lambda d\lambda}{\int J_\lambda d\lambda} \tag{57.12}$$

and

$$D = -\log_{10}\left[\frac{\int J_\lambda T_\lambda d\lambda}{\int J_\lambda d\lambda}\right] = \log_{10}\left[\frac{\int J_\lambda d\lambda}{\int J_\lambda T_\lambda d\lambda}\right] \tag{57.13}$$

The integration limits are set by the distributions.

From the above analysis, it is clear that in order to obtain meaningful density values, the spectral characteristics of the densitometer must be made equal to those of the receiver that will "view" the sample in actual use. Furthermore, of course, the actual receiver will vary from application to application. The densitometer characteristics are set by inserting appropriate filters in the beam. A number of spectral distributions are specified in Reference 1c as follows:

1. For reflection densitometry, the influx spectrum shall be ICI Illuminant A, which is essentially 2856 K.

2. For transmission densitometry the influx spectrum shall be Illuminant A modified by an infrared absorbing filter, as tabulated in the standard.

3. For samples to be viewed by an observer, the spectral characteristic of the system shall match the relative luminosity function $V(\lambda)$. This case is termed "visual" density.

4. For color negative films, a set of three distributions in the red, green, and blue regions of the spectrum is specified. This set is identified Status M, and approximates the spectral sensitivities of the three layers of color print materials.

5. For measuring red, blue, and green densities of color materials other than color negatives, a set of three responses identified Status A is provided.

6. To evaluate color images to be used in graphic arts processes, two sets of distributions are specified and are identified as Status T and Status E.

7. In the microfilm industry, prints are often made onto diazo or vesicular films. A narrow distribution centered at 400 nm is specified for this application, and the resulting densities are termed ISO printing densities Type 1.

8. A spectral distribution covering the range $\lambda \approx 360$ to 540 nm is provided for measuring samples to be printed onto B&W photographic papers. Such densities are designated ISO printing densities Type 2.

9. Status I response consists of three passbands centered at 420, 535, and 625 nm ±5 nm. This set is used in evaluating graphic arts materials such as process inks on paper.

10. A narrowband response centered at 800 nm ± 20 nm is provided for measuring effective densities to S-1 photosurfaces, such as those used in optical sound systems. Densities measured with this response are identified "ISO type 3."

These responses are shown in Figures 57.9a–e, which are reproduced from the current standard.

The next problem in color densitometry stems from the fact that the three layers are superimposed and from the nature of the dyes. The spectrophotometer curves for a typical dye set are shown in Figure 57.10. In this figure, the lower three curves refer to the dyes measured individually, while the upper curve shows the result of superimposing them. The values for the individual dyes are termed "spectral analytical densities," and those for the tri-pack are termed "spectral integral densities." Since superimposed densities may be considered to add, at any wavelength the spectral integral value is the sum of the three analytical values. Note that all three of the individual dyes absorb light outside the spectral regions in which they are supposed to work.

This unwanted absorption can cause problems in color reproduction and, more to the point for this chapter, in densitometry, because straightforward measurements of a real film at any wavelengths yield integral values. In many cases, these integral values are required. In the manufacture and processing of films, however, it may become necessary to determine the densities in an individual layer. It is not sufficient to coat and measure a layer by itself, since layers coated in a tri-pack may respond differently from the same layers operated singly.

This problem is solved by taking advantage of two rules called the "additivity rule" and the "proportionality rule." The first of these is merely the rule that densities add. The proportionality rule is an extension of Beer's law. Consider an element, such as a glass cell or a layer of a color film, containing a dye whose concentration can be varied. Beer's law states that
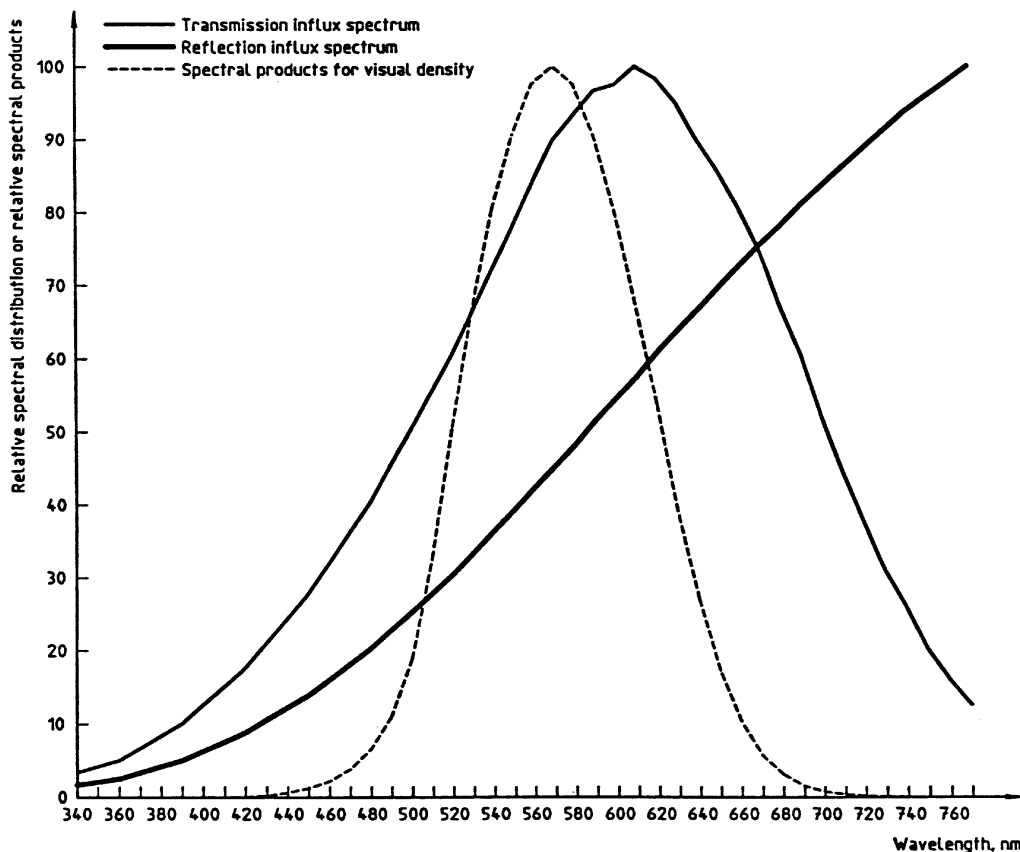
FIGURE 57.9a Spectral products for ISO density and relative spectral power distributions for influxes. *(continues)*

$$T_\lambda = e^{-\beta_\lambda c} \tag{57.14}$$

where c is the dye concentration and β_λ is the extinction coefficient at wavelength λ. The coefficient β varies with wavelength, of course, but will be constant at a given wavelength (unless changes in dye concentration produce chemical reactions.) Strictly speaking, Beer's law applies to the internal transmittance, but in the case of photographic layers, the surface reflectance is negligible. From Equation 57.14, it follows that

$$\ln T_\lambda = -\beta_\lambda c \tag{57.15}$$

and therefore,

$$D_\lambda = 0.434\beta_\lambda c \tag{57.16}$$

Consider now the density at two wavelengths for any given dye sample. Clearly,

$$\frac{D_{\lambda 1}}{D_{\lambda 2}} = \frac{\beta_{\lambda 1}}{\beta_{\lambda 2}} \tag{57.17}$$
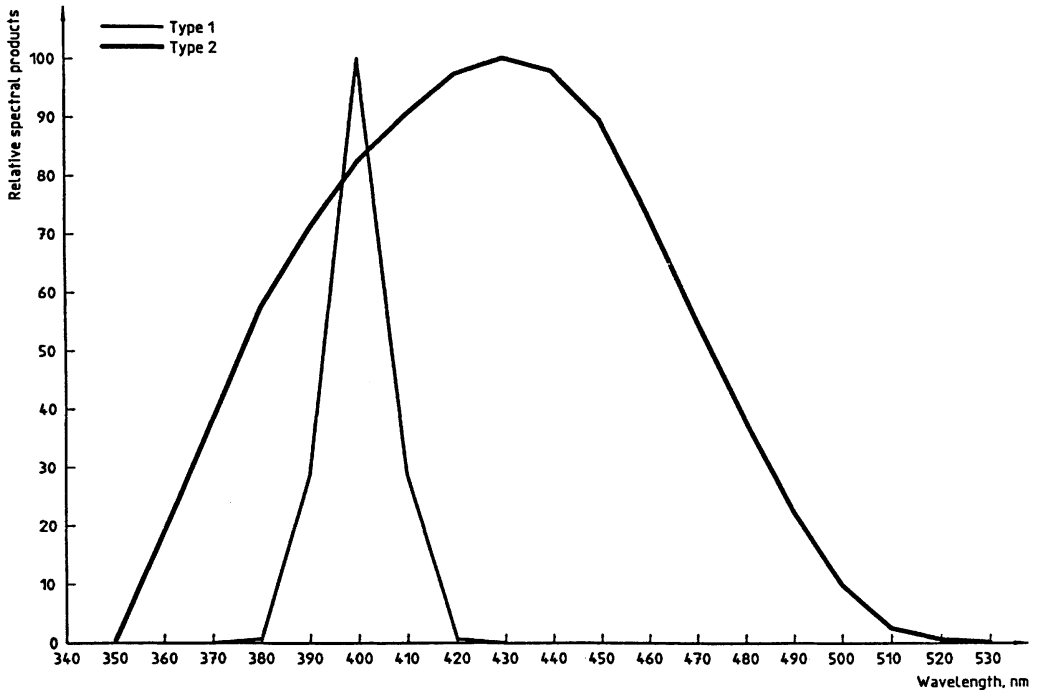
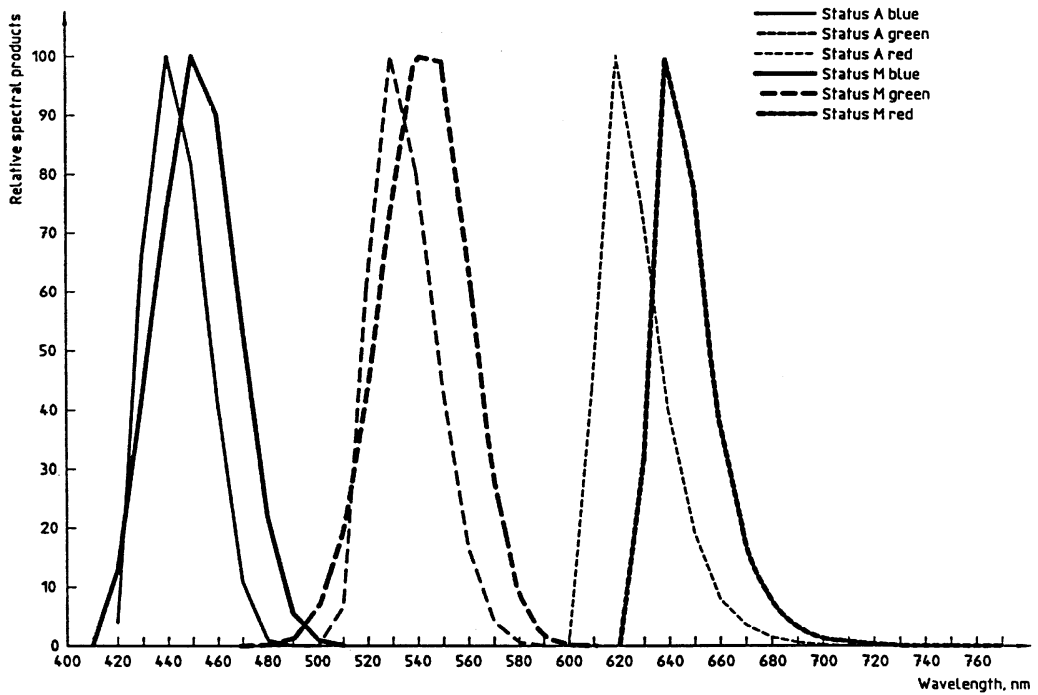**FIGURE 57.9b** Spectral products for type 1 and 2 densities. *(continues)*

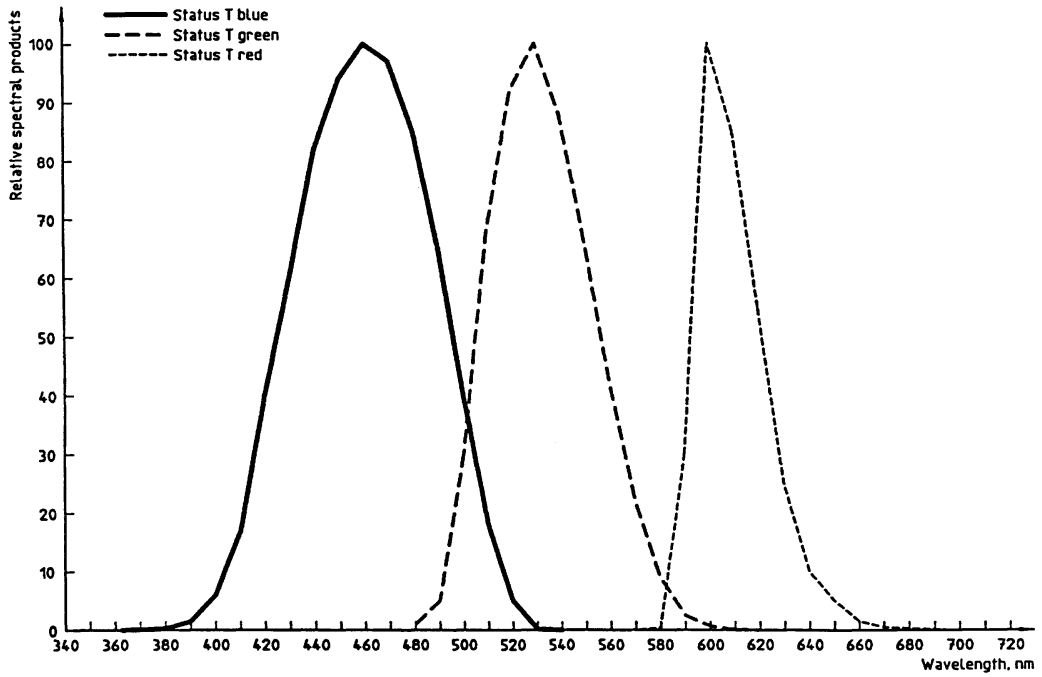**FIGURE 57.9c** Spectral products for Status A and M densities. *(continues)*

FIGURE 57.9d Spectral products for Status T densities. *(continues)*
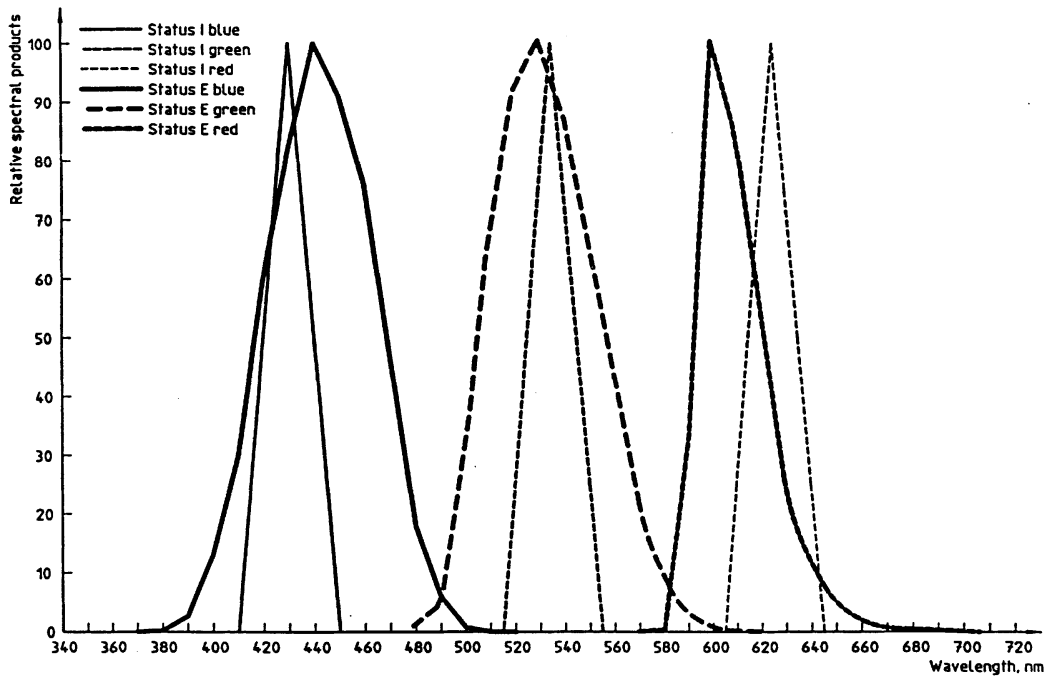

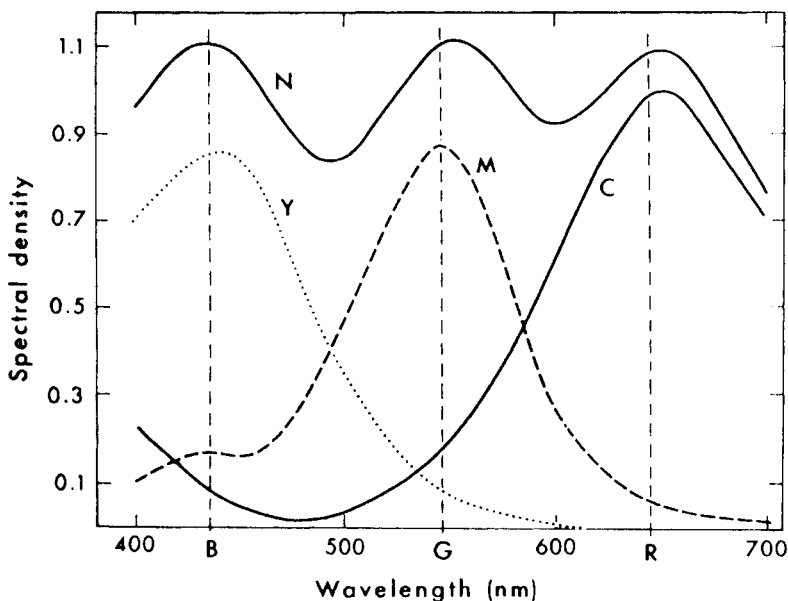**FIGURE 57.9e** Spectral products for Status E and I densities.

FIGURE 57.10 Spectral density distributions of the C. M, and Y components as functions of wavelength for a hypothetical color film, and of the composite absorber (N).

Thus, for a given dye sample, the ratio of the densities at any two wavelengths is fixed regardless of dye concentration (i.e., assuming Beer's law holds), and this is a statement of the proportionality rule.

As noted, straightforward density measurements on a real sample yield integral densities. The proportionality rule can be used to derive analytical densities in the following manner [12]. Assume spectral densities for simplicity. With reference to Figure 57.10, we select three wavelengths at or near the peak absorptances of the three dyes. Consider first the blue wavelength. By the additivity rule, the blue integral density is

$$D_b = Y_b + M_b + C_b \tag{57.18}$$

where Y_b, M_b, and C_b are the blue analytical densities of the yellow, magenta, and cyan dyes, respectively. But by the proportionality rule, $M_b/M_g =$ constant, where M_g is the analytical density of the magenta dye measured at the peak wavelength in the green. The value of this ratio is readily determined from a spectrophotometric curve of the dye. Denoting such ratios a_n, for measurements at the three peak wavelengths we have

$$D_b = Y_b + a_1 M_g + a_2 C_r$$

$$D_g = a_3 Y_b + M_g + a_4 C_r$$

$$D_r = a_5 Y_b + a_6 M_g + C_r \tag{57.19}$$

This constitutes a set of three equations with three unknowns. The solution has the form

$$Y_b = b_1 D_b + b_2 D_g + b_3 D_r$$

$$M_g = b_4 D_b + b_5 D_g + b_6 D_r$$

$$C_r = b_7 D_b + b_8 D_g + b_9 D_r \tag{57.20}$$

where Y_b, M_g, and C_r are the desired values of the three analytical densities. The *b*-coefficients are algebraic combinations of the *a*-coefficients, which can be reduced to numerical values since the *a*-coefficients are known. In practical work, the determination of the *a*-coefficients is usually done using data for a number of different dye density levels. The off-peak density for each level is plotted against the peak density, giving a straight line whose slope is a good measure of the *a*-coefficient. Thus, for example, the coefficient a_1 in Equation 57.14 would be found by plotting M_b vs. M_g for several levels. The values of the coefficients can also be found by doing narrow-band densitometry on the samples instead of spectrophotometry.

So far, we have been assuming spectral densities. By the first law of densitometry, however, any sample should be measured with a system whose spectral response is equal to that used in actual practice—in other words, color negative samples should be measured with the Status M filters described before, etc. However, the analysis described above works satisfactorily with the status filters, which are relatively narrow-band, and much practical densitometry is performed in this manner.

Finally, because of its practical importance, we must introduce one more type of color density: the "equivalent neutral density," or END. END is defined as the neutral density that a given dye deposit—either yellow, magenta, or cyan—will produce when it is combined with the correct amounts of the other two dyes, whatever those amounts may be. It is important in practical film building, because one of the most important properties of a color film is its ability to produce a neutral as a neutral—in other words, to image a gray object as a gray that shows no residual tint of another color. Such a film is said to be "balanced," and good balance is considered extremely important by discriminating users. When the ENDs of the three layers of a color film are equal, the image will indeed be balanced, and color film sensitometry may be done in terms of ENDs. The END is a form of analytical density because it is a property of an individual layer. Originally, ENDs were measured in a special densitometer, but they are now calculated from the normal analytical densities by an equation of the form

$$\text{END} = m[\text{analytical spectral density}] + K \tag{57.21}$$

where the constants m and K are determined by comparing the visual densities of satisfactory neutral images with the corresponding analytical spectral densities. In some cases, a second-order equation has been found to yield better results [12b].

57.5 Color Reflection Densitometry

Color reflection densitometry follows the general principles set forth above for the B&W reflection case. Since color prints are for the most part intended to be viewed by a human observer, in many cases a visual integral density provides the needed information. The film builder or process controller, however, may need information about the analytical densities of his layers, and here the approach used for transmitting samples does not work. The reason it fails is that, for such samples, Beer's law fails, as is shown by the curve of Figure 57.8. If the law held, the reflection density would be proportional to the dye concentration (see Equation 57.11).

Pinney and Vogelsong [13] have described a method of obtaining reflection analytical densities in such cases. The method involves the empirical determination of a calibration curve similar to Figure 57.8 for the material at hand, relating the reflection densities of a dye deposit to the transmission densities. The reflection integral densities of the sample are then measured and converted to transmission densities. The analytical values for these transmission densities are calculated using the method described above for such samples. Finally, the derived transmission values are converted back to reflection analyticals by going through the calibration curve in the reverse direction.

One last comment on the densitometry of color print papers should be added. In the commercial production of color prints, it may be extremely important to measure chemical stain in what should be the white areas of the picture. The passbands of the Status A filters are not well placed to monitor such stain, and it may be necessary to make additional measurements.

57.6 Densitometry of Halftone Patterns

Halftone patterns are used in the printing industry to reproduce continuous-tone images using two levels of ink: either ink or no ink. Various gray levels are produced by printing a pattern of repetitive "dots" too small to be resolved by the unaided eye. Essentially, the size of the dots is varied to produce a gray scale. Halftone patterns to be measured may be transmitting or reflecting; monochrome or color. A number of standards for densitometry in the graphic arts have been approved or are under development [14]. These standards provide much practical guidance, and are consistent with ISO-5. Densitometry in this field is an example of the basic mechanism by which the instrument operates—comparing the flux reaching the sensor with and without the sample in place. When the sample is a halftone, the flux reaching the sensor depends on the fractions of the area that are dense and clear. Adopting the notation of Ref. 13b and assuming a transmitting sample, the measured density will be

$$D_t = -\log_{10}\bar{T} = -\log_{10}[fT_s + (1-f)T_b] \tag{57.22}$$

where D_t = measured density of pattern, $\bar{T}$ = average pattern transmittance, f = fraction of pattern area that is dense, T_s = transmittance of "solid" areas (essentially equal to dot density), and T_b = transmittance of clear areas.

It is interesting to calculate the measured density of a halftone pattern half of which is perfectly dense ($D = \infty$; $T = 0$) and half of which is perfectly clear ($D = 0$; $T = 1$). The calculated value for $D \approx 0.3$; and this value will indeed be found if such a pattern is densitometered.

If D_t, T_s, and T_b are known, Equation 57.22 provides an easy way to determine the fractional area covered by the pattern dots with an ordinary densitometer, and this is often done in graphic arts work. In practical work, T_s and T_b are measured in terms of density also, and this can be done satisfactorily on large areas. Since by definition $T = 10^{-D}$, the solution of Equation 57.22 for f can be written

$$f = \frac{1 - 10^{-(D_t - D_b)}}{1 - 10^{-(D_s - D_b)}} \tag{57.23}$$

In this form, the equation is known as the Murray-Davies equation.

57.7 Summary

A densitometer measures the flux reaching the sensor with a sample in place, and calculates the ratio of this value to that obtained either with no sample in place (in the transmission case) or with a reference white in place (in the reflection case). The instrument then displays the negative log of this value.

The observed reading may depend significantly on the characteristics of the instrument, i.e., on the

1. angular substance of the influx beam,
2. angular substance of the efflux beam,
3. spectral power distribution of the influx beam, and
4. spectral sensitivity of the receiver.

For a complete specification of the density in a given case, these four parameters should be indicated. ISO 5.1. (Ref.1a) provides a standardized notation.

References

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a. Part 1: Terms, Symbols and Notations ISO5/1-1984.

b. Part 2: Geometric Conditions for Transmission Density ISO5-2, 3rd ed., 1991.

c. Part 3: Spectral Conditions. ISO5-3, 2nd ed., 1995.

d. Part 4: Geometric Conditions for Reflection Density. ISO5-4, 2nd ed., 1995.

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b. P. Kowaliski, in T. H. James (ed.), *The Theory of the Photographic Process, 4th ed.*, New York: MacMillan, 1977, Chap. 18.

13. J. E. Pinney and W. F. Vogelsong, *Phot. Sci. Eng.*, 6, 367, 1962.

14. American National Standards, New York: American National Standards Institute. A number of additional standards were under development by the Committee for Graphic Arts Technology Standards (CGATS) as of late 1997.

a. CGATS.4-1993: *Graphic Technology, Graphic arts reflection densitometry measurements, Terminology, Equations, Image Elements and Procedures.*

b. CGATS. 9-1994: *Graphic Technology, Graphic Arts Transmission Densitometry Measurements, Terminology, Equations, Image Elements and Procedures.*

Appendix

A. Sources of Densitometers

Gretag–Macbeth
617 Little Britain Road
New Windsor, NY 12553-6148

X-Rite, Inc.
3100 44th Street SW
Grandville, MI 49418

Camag
Sonnenmattstr 11
CH-4132 Muttenz
Switzerland

Note: Makers of densitometers are listed in the *Photonics Buyers Guide*, published annually by Laurin Publishing Co., Inc., Berkshire Common, P.O. Box 4949, Pittsfield, MA 01202-4949.

B. Aids to densitometry

1. Status and Other Filters
   Gretag–Macbeth

   X-Rite, Inc.

   Eastman Kodak Co.
   Scientific Imaging Products
   343 State Street
   Rochester NY 14650

2. Standard Reference Materials, Calibration Samples
   Gretag–Macbeth

   X-Rite, Inc.

   Graphic Communications Association
   100 Dangerfield Road
   Alexandria VA 22314

   PSI Associates
   3000 Mount Read Boulevard
   Rochester, NY 14616

   Lucent Technologies
   235 Middle Road
   Henrietta NY 14467

   National Institute of Standards and Technology
   Gaithersburg MD 20899

   Eastman Kodak Co. Provides densities on film calibrated to ±5% or ±0.02 density unit, whichever is greater.