Exposure is defined as the product of image illumination and effective exposure time.

$$E \cdot t = H$$

E = Image Illuminance
t = Shutter Speed
H = Film Plane Exposure

For values representing mean values subtext "g" is added to the variable so the basic camera exposure equation for mean exposure is:

$$E_g \cdot t = H_g$$

Assumptions:
$E_g = 8$
$t = 1/ISO$

E doesn't represent just the scene but the camera's optical system as well. The equation for E breaks down as:

$$E = \frac{L}{A^2} \cdot \left[\frac{\pi}{4} \cdot \left(\frac{U - F}{U} \right)^2 \cdot \tau \cdot C \cdot V \cdot \cos(\deg \cdot \theta)^4 \right]$$

L = scene luminance in nits
U = distance from lens to object
F = focal lenght of lens
τ = lens transmittance
C = camera flare correction factor
V = vignetting factor
θ = angle of image point from axis of lens
A = f/number of lens aperture system

Assumptions:
$L_g = 297 * 10.76$
$A = 16$
$F = 50$
$U = 80*F$
$V = 1.0$
$C = 1.03$
$\theta = 12$
$\tau = .90$

The E equation is usually simplified and split into two.

One part is the scene luminance divided by the f/stop.

$$\frac{L}{A^2}$$

The second part is the optical system defined by the constant q.

$$q = \frac{\pi}{4} \cdot \left(\frac{U - F}{U} \right)^2 \cdot \tau \cdot C \cdot V \cdot \cos(\deg \cdot \theta)^4 \qquad q = 0.65$$

Through-lens-metering systems don't need q because they measure the actual amount of light striking the back of the camera. Calculating H with anything other than a TTL system requires factoring q which is an representation of average camera conditions. The part of the equation with U is equivalent to focusing the lens at infinity. A camera focused nearer than infinity will change the actual value of q. But q is considered to be a constant and doesn't change.

The camera exposure equation then becomes:

$$E = \frac{q \cdot L}{A^2}$$

Mean camera exposure is:

$$E_g = \frac{q \cdot L_g}{A^2}$$

The hand held light meter is in the same situation. It is used outside the camera's optical system and therefore the optical system has to assume average optical conditions, but being a tool itself, it also has elements that need to be addressed in order to accurately predict correct camera exposure. The optical elements from q are incorporated into the variables from the meter creating a new meter constant K. (part 2)

Defining K, Part 2

K is very similar to q in that they can be considered a light loss constants, but K works in an opposite manor than q. While q takes the value for the luminance of the subject and factors in the reduction of illuminance to what is produced at the film plane. K takes what the luminance value should ideally be and calculates what the luminance needs to be to make the required exposure.

This relationship can be seen in the standard's calibration equation.

$$\frac{A^2}{T} = \frac{B \cdot S}{K}$$

where
A = aperture
T = shutter speed
B = luminance, footcandles
S = Film speed
K = Exposure Constant

Let's break down the equation and figure out what the ideal luminance is. After removing K and structuring the equation to solve for B, we apply Sunny 16 numbers. B_1 is the "ideal" luminance value.

$$\frac{A^2}{T} = B_1 \cdot S \qquad \frac{A^2}{(T \cdot S)} = B_1 \qquad \frac{256}{\left(\frac{1}{125}\right) \cdot 125} = 256 \qquad B_1 = 256 \qquad A^2 = B_1$$

If the optical influence of the lens were eliminated, B would equal A^2. As the luminance of the subject is lost do to various variables (which are the variables defined in q), the actual subject luminance needs to be slightly higher. To determine how much higher, we need to look to L_g in the equation for E_g.

$$L_g = 297 \qquad B = 297 \qquad \frac{297}{256} = 1.16 \qquad K = 1.16\ cd/ft^2 \ \text{ or } \ K = 12.5\ cd/m^2$$

In other words $A^2 = \frac{B}{K}$ and $A^2 \cdot K = B$

The equation for K. In part 3, we'll break it down and look at the component variables.

$$K = \frac{4 \cdot K_1 \cdot U^2 \cdot r}{(U - f)^2 \cdot t \cdot C \cdot H \cdot \cos(\theta)^4 \cdot p \cdot R \cdot 10.76 \cdot \pi}$$

Variables:

t = 0.90	r = 1.00
f = 50	R = 1.00
K_1 = 8.11	C = 1.03
U = 80	H = 1.00
θ = 12	p = 1.00

Nomenclature:
U = 80*f - Distance from lens to object
f = 50mm - Focal length of lens
t = 0.90 - lens transmittance
C = 1.03 Camera Flare Correction factor at Hg
H = 1.00 - Vignetting factor
θ = 12° - angle of image point from axis of lens $\cos^4\theta = 0.916$
A= 16 - f-number of lens aperature
K_1 = 8.11 - Constant - when R,p,r = 1 $K_1 = H_g$
R = 1.00 - Luminance distribution factor
p = 1.00 - ratio of spectra response between scene luminance and senstitometric illuminance.
r = 1.00 photocell's spectral response

$$\frac{4 \cdot K_1 \cdot U^2 \cdot r}{(U - f)^2 \cdot t \cdot C \cdot H \cdot \cos(\deg \cdot \theta)^4 \cdot p \cdot R \cdot (10.76 \cdot \pi)} = 1.16 \qquad \frac{4 \cdot 8.11 \cdot 1.00 \cdot 1.025}{.90 \cdot 1.03 \cdot 1 \cdot .916 \cdot 1 \cdot 1 \cdot (10.76 \cdot \pi)} = 1.16$$

Defining K, Part 3a - Relation Between Basic Exposure Parameters

Most of this part comes from Appendix C in ANSI PH3.49 – 1971, for General Purpose Photographic Exposure Meters. I've updated two variables from the standard - from E_g to H_g, and from I to E.

Nomenclature:
U = 80*f - Distance from lens to object
f = 50mm - Focal length of lens
t = 0.90 - lens transmittance
C = 1.03 Camera Flare Correction factor at Hg
H = 1.00 - Vignetting factor
$\theta = 12°$ - angle of image point from axis of lens $\cos^4\theta = 0.916$
A= 16 - f-number of lens aperature
$K_1 = 8.11$ - Constant - when R,p,r = 1 $K_1 = H_g$
R = 1.00 - Luminance distribution factor
p = 1.00 - ratio of spectra response between scene luminance and senstitometric illuminance.
r = 1.00 photocell's spectral response

Classic camera image illuminance equation:

$$E_g = \frac{B\cdot(U-f)^2\cdot t\cdot C\cdot H\cdot \cos(\theta)^4}{4\cdot A^2\cdot U^2}$$

Equation for determination of K

$$K = \frac{4\cdot K_1\cdot U^2\cdot r}{(U-f)^2\cdot t\cdot C\cdot H\cdot \cos(\theta)^4\cdot p\cdot R\cdot 10.76\cdot \pi}$$

Both the equations are similar except the equation for K contains four additional variables (highlighted), K_1, r, p, and R.

First let's take a look at the other variables. U and f together represent a lens focused at infinity. Together they form

$$\left(\frac{U}{U-f}\right)^2 = 1.025$$

It will always equal 1.025 no matter the focal length. Any one shooting large format is familiar with bellows extension. Exposure is reduced when the length of the bellows exceeds the focal length of the lens. The standard's equation assumes focus at infinity.

C is a correction factor for flare at H_g. As the point of exposure increases, flare decreases, so while average flare in the shadows is around one stop, by the time it reaches Hg, it is around 3% or 1.03. I added the part about H_g in the nomenclature definition for clarity and it holds true for the camera image equation, but the optical system in spot meters might change the value of C in the K equation.

t is the light transmitted through the lens. At 0.90, it assumes 90% of the light entering the lens passes through it. H is the vignetting factor. It's value of 1 or unity means that it isn't factored in. And θ has the angle of the image from the axis at 12 percent. I assume that has been considered a good average between axis and more extreme angles.

Most of the variables above are considered to be very consistent, but technically if any of the variables have a different value, the value of K will change. TTL meters automatically adjust for these variables, but a hand held light meter can't. It must assume user adjustment in the case of bellows extension, or minor and acceptable variance in value of the variable.

Part 3b will finish with evaluating the variables in the K equation with three of the variables are most likely the cause of the varying K factors in meters, and a very familiar value for K1.

The variables R, p, and r perhaps may have the greatest influence on the value of K, but how much has to remain speculative because they fall under the umbrella of manufacturer testing and manufacturers are notoriously secretive about internal information.

Equation for determination of K

$$K = \frac{4 \cdot K_1 \cdot U^2 \cdot r}{(U-f)^2 \cdot t \cdot C \cdot H \cdot \cos(\theta)^4 \cdot p \cdot R \cdot 10.76 \cdot \pi}$$

K_1 = 8.11 - Constant - when R,p,r = 1 $K_1 = H_g$
R = 1.00 - Luminance distribution factor
p = 1.00 - ratio of spectra response between scene luminance and senstitometric illuminance.
r = 1.00 photocell's spectral response

Luminance Distribution Factor – R

According to the 1971 ANSI light meter standard, "This factor is of importance when the background luminance within the field is radically different from the subject luminance. In this kind of scene, a meter reading may not lead to the best picture. The best picture would be obtained by setting into the meter's calculator a reading based on some other luminance value B_d, and giving the exposure directed by the calculator."

Re-evaluation of Factors Affecting Manual or Automatic Control of Camera Exposure, is a paper written previously to the 1971 standard, where one of it's authors was the committee chairman of the 1971 standard, and much of the paper's appendix directly taken from the paper. It goes into a little more detail. "The preferred exposure is obtained when the maximum luminance represented by the brightest area of interest in the scene and the minimum luminance, represented by the darkest area of interest n the scene are desirably spaced on the density-log exposure curve."

"It has been found by experience that this spacing occurs when the exposure resulting from the minimum luminance (Bmn) is located some distance X from the shoulder, and the exposure resulting from the maximum luminance (Bmax) occurs the same distance X on the other side of the toe point of the curve."

In other words, Hg is at a point where the average luminance range falls on the curve to reproduce the tones of the subject with some degree of quality. If the scene's luminance distribution is different enough to shift the exposure away from Hg, then there needs to be an adjustment – R.

It's impossible to know any of the assumed values for the variables that make up ba do once again to the secrecy of manufacturers; however, see what the contributing variable are and their relationship is helpful.

The equation for R is: (some of the nomenclature is outdated)

$$R = \frac{B_a}{D_d}$$

Where
Bd = value of luminance which would lead to the best picture
Ba = field luminance as measured by the meter

Ba breaks down into

$$B_a = \frac{C_a \int_{C_s}^{B_s} da}{a}$$

Where
Ca = cell acceptance of the ratio of the luminance of the field measured by the system to the illuminance on the bare cell when both result in the same scale indication.
a = area of the scene
Ic = cell illuminance
Bs = luminance of any particular point in the scene
Cs = cell acceptance for light from the same particular point.

Spectral Considerations - r and p

The ANSI standard defines spectral consideration as "the spectral response of the film and the detector as well as the spectral quality of the light in the scene, and the light used in calibration and sensitometry, affect the meter calibration."

The variable r is part of the short hand K equation indicating that it might be one of the major factors in any variance of K. The standard defines it as "r is chosen to relate the photocell's spectral response to the scene as compared to that in calibration. r = ratio of luminance of uniform surface source used in calibration to luminance of scene when both sources produce the same response of the meter. Since the calibration color temperature of 4700K was chosen to minimize the spectral effect of indicated luminance in daylight compared to the indicated luminance for tungsten, the spectral response ratio determined between 4700K and 2850K is reasonable measure of the effect of difference in spectral sensitivity between daylight and the 4700K calibration sources."

The meter needs to be calibrated to a light source that represents real world usage, but the meters are used in a wide range of color temperatures. Added to this is the spectral bias of the photocell. The standard needs to take into account the spectral range and spectral sensitivity and somehow come up with a way that will produce an acceptable exposure in as many different situations and meters as possible with as little variance as possible. In Allen Stimson's paper An Interpretation of Current Exposure Meter Technology, he has a nice long section on the change of the color temperature of the calibration light source from 2850K used up until sometime in the 1960s to 4700K still used today.

B&W films used to have an ASA plus an EI for shooting under tungsten light and an EI for shooting under Daylight. This mostly had to do with the color temperature of the calibration luminance source and the spectral sensitivity of the exposure meter's photo cell. Testing eventually found errors could be equally divided between daylight and tungsten if all meters were calibrated at 4700 degrees Kelvin. Fig 3.

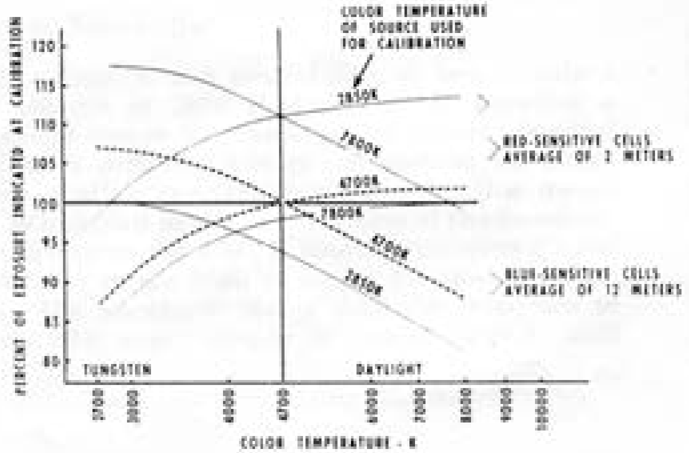


Fig. 3. Meters which are calibrated at 4700°K are more accurate over the entire range than those calibrated at tungsten or daylight color temperatures.

According to An Interpretation of Current Exposure Meter Technology, "with changes in color temperature, the sensitivity of selenium cells of American manufacturers changes in the same direction, although somewhat less in magnitude, as panchromatic negative materials. Hence, meter makers have urged film manufacturers to eliminate tungsten film ratings for several years."

"Kodak Research Laboratories made extensive tests on a dozen of each of fourteen makes for meters to determine the feasibility of this elimination. Their tests showed that two of the fourteen changed sensitivity with color temperature in the opposite direction from the majority. This confirmed other observations that some meters, which manifested perfect calibration in the laboratory (at 2700K), differed markedly when used in daylight."

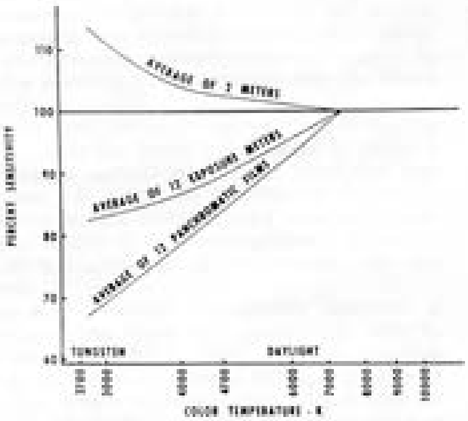


Fig. 2. Change in average spectral sensitivity with color temperature of 12 panchromatic films and 14 exposure meters.

I have to admit that I'm not familiar with the different spectral characteristics of photo cells or their history, but I do know that photo cells made up of different materials will have different spectral biases. Selenium cells appear to have a greater sensitivity to blue light. If they were in common use before the 1960s, this could account for the standard's calibration temperature of 2850K in order to attempt to balance out the bias. Pentax's user manual has a silicon photo diode as its photo cell. I assume that would be the silicon blue in the examples from Photographic Materials and Processes.

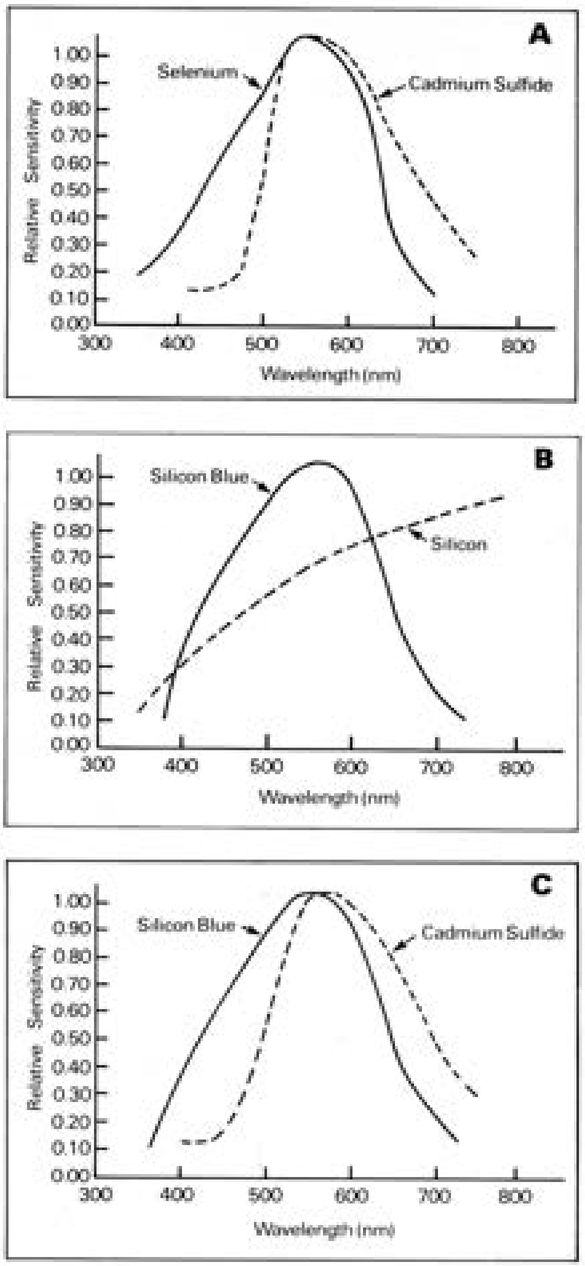


Figure 3–33 *Spectral sensitivity of selenium, cadmium, sulfide, and silicon exposure-meter cells. (A) Spectral sensitivity curves for selenium cells and cadmium sulfide cells. Cadmium sulfide cells have much higher overall sensitivity, which is not revealed because the curve heights have been adjusted, but the spectral sensitivity of selenium cells more closely matches that of panchromatic films. (B) Silicon cells have high red sensitivity and low blue sensitivity, but the spectral sensitivity balance is improved in silicon blue cells through the use of filters. (C) A comparison of the spectral sensitivity of silicon blue cells and cadmium sulfide cells.*

Also from Current Exposure Meter Technology, " One of the two manufacturers of meters having red-sensitivity cells has found it necessary to assign a higher speed to certain color films than the film manufacturer. It is obvious that the red-sensitivity of the cells causes the meter to read relatively lower in daylight resulting in overexposure. A higher film speed was assigned to compensate for the discrepancy."

As one exposure meter must fit the needs of a wide range of film types, from b&w negatives to color reversal, it's always easier to change the film's ISO or EI than the exposure meter to match each situation. r is the adjustment to compensate for the majority of conditions. Stimson's paper, Re-evaluation of Factors Affecting Manual or Automatic Controls of Camera Exposure, has a range of values for r for meters with two types of photo cells:

Selenium Cells – r = 1.0 to 1.2
K = 1.16 to 1.40

Cadmium sulfide cells – r = 0.8 to 1.0
K = 0.93 to 1.16

I'm assuming that r is an average for scenes over a range of color temperatures

According to the ANSI 1971 Standard, "this factor K_1 has been determined experimentally by psychometrically selecting the "preferred exposure" for scene types, light levels, and camera and meter types covering the ranges normally encountered. " K_1 comes from the psychophysical testing by Loyd Jones in his First Excellent Print Test and similar consequent psychophysical testing.

If anyone remembers the basic exposure equation from part 1:

$$H_g = E_g \cdot t$$

Where
Hg = Mean exposure at the film plane
Eg = Mean Image illuminance
T = Shutter speed

When t is equal to 1/ISO K_1 can replace E_g making the equation:

$$H_g = K_1 \cdot t \quad \text{or} \quad H_g = \frac{K_1}{S_x}$$

Where
S_x = film speed

What this means is that within the equation for K sits the aim illuminance value Eg for camera exposures. This should prove to anyone that K isn't an arbitrary value. It is directly related to a determined exposure value. But the version of K in the K equation is $K`_1$ which is the value of K_1 when:

R=1.0
p = 1.0
r = 1.0

$$H_g = K'_1 \cdot \frac{r}{p \cdot S_x \cdot R}$$

Please note that in the K equations from in the previous parts, I had $K`_1$ as $K_1$. It should be $K`_1$.

$K`_1$ becomes a constant for the exposure value that all exposure meters aim for. Specific f/stop and shutter speed exposure is calculated using the exposure meter's calculator, but the exposure meter itself is calibrated to make one specific exposure value and that is $K`_1$. This way a single meter can be used for each type and speed of film, from b&w negatives to color transparencies. For each film type to be able to work with the meter, the speeds must be calculated in accordance with the constant $K`_1$ (which will be covered in more detail in the next part).

The value of K`1 is another matter. Mathematically solving for K`1 from the K equation, K`1 equals 8.11. The constant for the camera exposure is 8. That's not a big difference and I believe that the difference comes simply from rounding.

The equation for K is finally complete. With $K`_1$ equaling 8.11, K = 1.16/12.5. This stands for the basic light loss of the basic optical system. A TTL system will require the same subject luminance and experience approximately the same loss of illuminance of 1.16 times between the luminance of the subject and the illuminance at the film plane as the calculation suggests from the exposure meter. It's the values greater or less than 1.16/12.5 that can be primarily attributed to the functionality of the meter and what can be attributed to any discrepencies between the hand held metered exposure and the camera exposure.

Most of the variables in the K equation are relatively consistent, but several have a tendency to change. Allen Stimson in Re-evaluation of Factors Affecting Manual of Automatic Control of Camera Exposure suggests creating a basic version of K by eliminating the variables subject to change from the K equation. The basic exposure constant of K is designated K_o, and the simplified K equation becomes.

$$K = \frac{K_o \cdot r}{t \cdot R}$$

Removing r,t and R from the K equation K_o equals 1.043.
r = 1.0
R = 1.0
t = 0.90

$$\frac{1.043 \cdot 1}{.90 \cdot 1} = 1.16$$

The 1971 standard's appendix appears to have not considered R to be necessary and the new simplified equation becomes:

$$K = \frac{K_o \cdot r}{t}$$

Considering that r and t are the two variables that Stimson considers likely to change, t is related to the camera and r to the light meter's spectral sensitivity, it's hard not to conclude that r which is the "photocell's spectral response to the scene as compared to that in calibration" is the principle factor in variations in the value of K.

In the next part, we'll be looking at the range of K, what reflectance does the meter read, and maybe how the constants q, K, and a new one P, relate.

Defining K, Part 4 - Range of K

We've established the value of $K = 1.16\ cd/ft^2$ and $12.5\ cd/m^2$ represents the standard value of K. But K can vary depending on the various conditions of the component variables that make up the K equation, most notably R, r, and t. I've only been able to find documentation on modern meters with $K = 1.16/12.5$ or $K = 1.30/14.0$ (all with a silicon photocell). But what is the acceptable range of K and how much does it affect the value of B (L in today's nomenclature)?

The 1994 exposure meter standard has two ranges for the value of K.

$B_o = 256$

Range 1

10.60 to 13.40 cd/m^2

1.00 to 1.245 cd/ft^2

$B_o \cdot 1.00 = 256$

$B_o \cdot 1.245 = 319$

Range of K_1

$\log(319) - \log(256) = 0.096$

The range of K_1 falls just under 1/3 stop

Difference between K = 1.16 and K = 1.245

$\log(319) - \log(297) = 0.031$

The difference is 1/10 stop.

Range 2

13.30 to 16.90 cd/m^2

1.236 to 1.57 cd/ft^2

$B_o \cdot 1.236 = 316$

$B_o \cdot 1.57 = 402$

Range of K_2

$\log(402) - \log(316) = 0.105$

The range of K2 is just over 1/3 stop

Difference between K = 1.16 and K = 1.57

$\log(402) - \log(297) = 0.131$

The difference is 4/10 stop.

What is the difference between K = 1.16/12.5 and K = 1.30/14.0?

$B_o \cdot 1.30 = 333 \qquad B_o \cdot 1.16 = 297$

$\log(333) - \log(297) = 0.05$

The difference in B (L) for the two most common versions of K on the market today is 1/6 stop.
In my opinion, it's not really all that much to be concerned about. At least not as much as Soylent Green being people.

In the next part, we'll look at where the whole light meters reading reflectance comes from and why it isn't relevant.

Now that we've covered the variables that make up K, it's time to connect K to exposure. The idea of the exposure meter is to substitute a single luminance value in the determination of the exposure to represent a multiplicity of luminance values of the scene itself. In other words, no matter the luminance range of a scene or how many individual measurements made from the scene, there can be only one luminance value placed into the exposure calculator to determine the camera exposure.

According to D. Connelly's paper Calibration Levels of Films and Exposure Devices, "In practice, exposure determined by this substitution is satisfactory only for what may be termed average scenes. From the point of view of the film, satisfactory photography depends upon the proper location on its exposure/density characteristic of the densities produced by the image illumination within the camera. The greatest and least significant luminances in the scene are required to cause exposure of the film within the usable part of its exposure/density characteristic. That implies that the important characteristics of the luminances are:

1. The ratio of its maximum to its minimum value (luminance range)
2. Its absolute value of maximum and minimum (the actual value of the min and max luminance values)

For the former determines whether or not the film can reproduce the contrast range of the scene and the latter determines the exposure time necessary to provide an exposure which will locate the brightness scale of the scene currently relative to the film characteristic."

So what Connelly is saying is that we need to determine the average luminance range and define how the range falls on the curve in relation to the single camera exposure value.

What is that camera exposure value? For that we need to go back to the calibration exposure meter equation:

$$\frac{A^2}{T} = \frac{B \cdot S}{K}$$

where	B = luminance, footcandles
A = aperture	S = Film speed
T = shutter speed	K = Exposure Constant

The exposure parameters are based on the camera set at f/16, on a clear sunny day with a solar altitude of about 40 degrees and the film speed equal to the reciprocal of the effective exposure time or Sunny 16. I like to use a film speed of 125 because it is the only film speed with an equivalent shutter speed 1/125.

We have determined that the standard value of K is 1.16 cd/ft^2 or 12.5 cd/m^2. That would make the value of B (modern L) which represents the luminance value for Lg in the camera exposure equation:

$$\frac{16^2}{\left(\frac{1}{125}\right)} = \frac{B \cdot 125}{1.16} \qquad \frac{A^2}{(T \cdot S)} \cdot K = B \qquad \frac{16^2}{\left(\frac{1}{125}\right) \cdot 125} \cdot K = 256 \cdot K \qquad 1.16 \cdot 256 = 297 \qquad B = 297$$

Now, plug the luminance value for B into the camera exposure equation (from part 1) where B becomes L_g. First without t, shutter speed, to determine the value for E_g and then factoring in t to derive H_g.

$$\frac{q \cdot L_g}{A^2} = E_g \qquad \frac{.65 \cdot 297 \cdot 10.76}{16^2} = 8.11 \qquad \frac{q \cdot L_g}{A^2} \cdot t = H_g \qquad \frac{.65 \cdot 297 \cdot 10.76}{16^2} \cdot \frac{1}{125} = 0.065$$

$$E_g = 8.11 \text{ cd/m}^2 \text{ or nits} \qquad H_g = E_g \cdot t \qquad H_g = 0.065 \text{ mcs or lux sec}$$

E_g has the equivalent value as $K`_1$ from the K equation. In fact they are the same variable just with different nomenclature. This value of 8.11 or the possible rounded value of 8 is what the meter with it's exposure calculator wants to place the exposure at if you assume shutter speed is the reciprocal of the film speed. As such, it becomes a constant exposure value with a new designation – P. While P = 8, for the purposes of keeping the maths right, we shall mostly be using 8.11.

Basically, the aim camera exposure for any ISO film can be calculated using:

$$H_g = 8 \cdot \frac{1}{ISO} \quad \text{or} \quad H_g = \frac{8}{ISO}$$

example:

$$\frac{8}{100} = 0.080 \qquad \frac{8}{125} = 0.064 \qquad \frac{8}{400} = 0.020$$

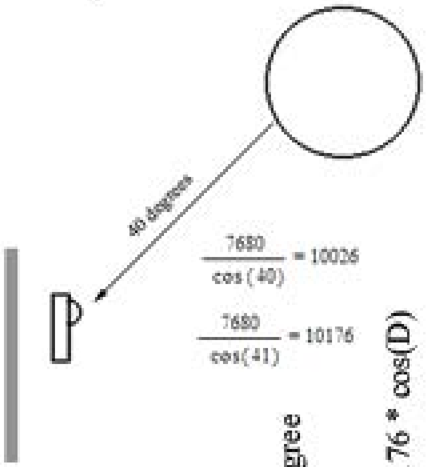
The placement of H_g is based on the assumption of an average luminance range and how it will fall on the curve in relation to what is considered necessary to produce a quality print. These parameters have been determined through psychophysical testing. In order to put it all into context, where L_g falls in relation to the luminance range of the scene and the relationship on the film curve, we first need to determine the average scene illuminance. For this, we turn once again to the exposure meter calibration equations, this time adding in the equation for incident meters.

$$\frac{A^2}{T} = \frac{B \cdot S}{K} = \frac{E \cdot S}{C}$$

Where
E = incident light, in footcandles (illuminance)
S = film speed
C = exposure constant

The standard has the basic value for C = 30, and the value of E becomes:

$$\frac{A^2}{(T \cdot S)} \cdot C = E \qquad \frac{16^2}{\left(\frac{1}{125}\right) \cdot 125} \cdot 30 = 7680 \text{ footcandles}$$



This value equals the illuminance measured from a solar angle of 40 to 41 degrees with the light meter held perpendicular to the subject. The actual value of the average illuminance with the meter at a solar angle of 0 degrees is 10,026 footcandles for 40 degrees and 10,176 for 41 degrees.

Degree	10176 * cos(D)
0	10176
10	10021
20	9562
30	8813
40	7795
50	6541
60	5088

Calibrated reflectance

Reflectance in photography is:

$$R = \frac{\text{Luminance}}{\text{Illuminance}}$$

But R implies a Lambertian surface which is a perfect diffuser so B(L) is:

$$R = \frac{L \cdot \pi}{E} \qquad R = \frac{B \cdot \pi}{E} \qquad \frac{297 \cdot \pi}{7680} = 0.121$$

It's also possible to find R using just the constants:

$$R = \frac{K \cdot \pi}{C} \qquad \frac{1.16 \cdot \pi}{30} = 0.121 \qquad \frac{12.5 \cdot \pi}{323} = 0.122$$

It should be obvious at this point that meters aren't calibrated to any reflectance. While you can imply a reflectance in relation between illuminance and luminance for the average luminance range as a conceptual reference point, this tends to help maintain the calibration misconception, but it also can help prove that they aren't. Incident light exposure meters generally have two different values for C and E. For example, Minolta's Meter III which has a C = 330 for the "spherical diffuser" and C = 250 for the "flat diffuser." Its value for is K = 14. The average reflectances would then become:

$$\frac{14 \cdot \pi}{330} = 0.133 \qquad \frac{14 \cdot \pi}{250} = 0.176$$

The value B (L) for the reflection exposure meter hasn't changed, only it's relation to the value of E for the incident exposure meters. I believe the difference in the values of C is because the flat disk is generally pointed directly toward the light source and is fully illuminated, while the hemispheric dome is pointed toward the camera with direct illuminance only partially covering it.

Exposure meters are calibrated to an luminance B (L). The exposure calculator then wants to take that luminance and produce $E_g = 8$ together with the shutter speed and f/stop reciprocal relationship based on the film speed to equal a single exposure value Hg for a given film speed regardless of the scene's illuminance. So, where ever I point the meter, it wants to produce an exposure of P/ISO or 8/ISO.

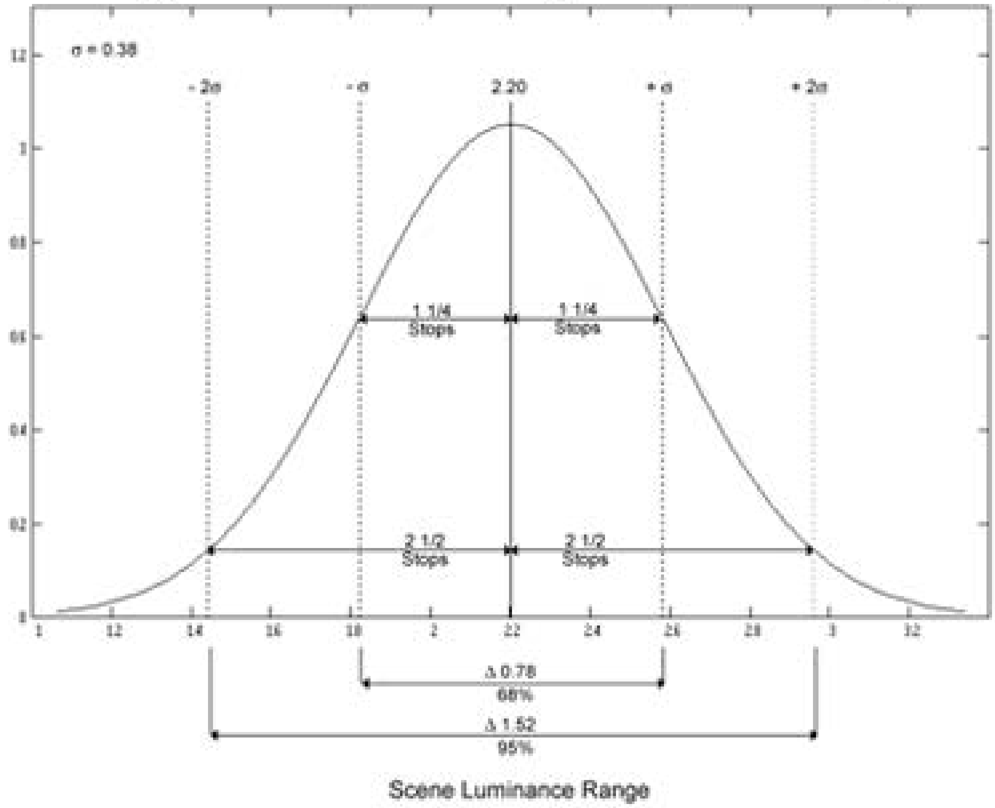
In my opinion, the Zone System's use of equating Zone V with a specific reflectance and relating it to the metered reading only reinforces the calibration misconception.

The next part will delve further in the importance of P and it's link to film speed. It will also cover the average luminance range placement on the film curve and their illuminance values that define the standard exposure model and explains the exposure's middle gray. And if there's space, it will introduce yet another constant, k, which expresses the relationship between sensitometric film speed exposure and P. This constant is perhaps the key to understanding the relationship between the speed of the film, the speed setting on the meter, and exposure.

Knowing the implied reflectance of the exposure meter can be useful in determining and confirming the luminance (L) and exposure (H) values for the standard model average luminance scene and it's placement on the film curve. Exposure is more than recording a single luminance value. L_g might be what the exposure calculation is based on, but it is only one value in a range of values. The placement of L_g must be considered in relation to how all the other luminance values will fall.

Average Luminance Range

This means determining an average scene luminance range. Variance in natural occurring phenomenon can be graphed on a normal distribution curve or bell curve. Sixty-eight percent of the sample population falls within the first standard deviation (-σ to +σ) and 95% falls within two standard deviations (-2σ to +2σ). Loyd Jones did an extensive survey over an 18 month period and found that the average exterior luminance range was 2.20 logs or 7 1/3 stops with a standard deviation of 0.38. In general usage 2.20 is commonly rounded down to 2.1 (7 stops) with no ill effects, but we need to keep it at 2.20 in order to better illustrating the concepts of photographic theory. For the record, the 2.20 log luminance range doesn't take in the entire range from deepest darkest crevice to bright specular reflection. It is from a dark tone of usable detail to a diffuse white containing some specular reflections.



The next step is to determine how the 2.20 log luminance range is distributed around Lg. It would seem logical to cut the range in two with 1.10 falling below and 1.10 falling above, but that isn't the case. The highlight is considered to have a 100% reflectance (RD 0.00) and the shadows falling 2.20 logs below at 0.631% reflectance. Remember, reflectance is based on a perfect diffuser. A surface with specular reflections can often exceed 100% reflectance.

We know when K = 1.16/12.5, L_g has a reflectance of 12% or an RD of 0.92 when compared to the incident light meter value for C or 7680 (it actually has a reflectance of .121 which equals an RD of 0.916 which is the value we will be using for calcualtions). That's a difference of 0.92 between L_g and the highlight luminance, L_h. That leaves 2.2 – 0.92 or 1.28 for the difference between L_g and the shadow luminance, L_s.

Exposure Renge and Exposure Placement

In order to see how these fall on the film curve we need to find the value for the illuminance value at the film plane, H, for each of the three reflectance values. This can be done by applying the values to the standard camera exposure equation, but first we need to determine their luminance values.

Equation to find luminance from reflectance and illuminance:

$$L = \frac{E \cdot R}{\pi}$$

Where
E = Scene illuminance
L = Luminance
R = Reflectance

I like to work from reflection density, so to convert RD to R I use:

$$R = \frac{1}{10^{RD}}$$

Finding the luminance values for L_h, L_g, and L_s

$$\frac{(7680) \cdot \frac{1}{10^{2.2}}}{\pi} = 15.42 \qquad \frac{(7680) \cdot \frac{1}{10^{.916}}}{\pi} = 297 \qquad \frac{(7680) \cdot \frac{1}{10^{0.00}}}{\pi} = 2445$$

$L_s = 15.42\ cd/ft^2$ $\qquad$ $L_g = 297\ cd/ft^2$ $\qquad$ $L_h = 2445\ cd/ft^2$

We now use the standard camera exposure equation to determine the values for the exposure at the film plane, H. I'm using a film speed of 125 because it is the only film speed that has a shutter speed equal to its reciprocal.

$$H = \frac{q \cdot L}{A^2} \cdot t$$

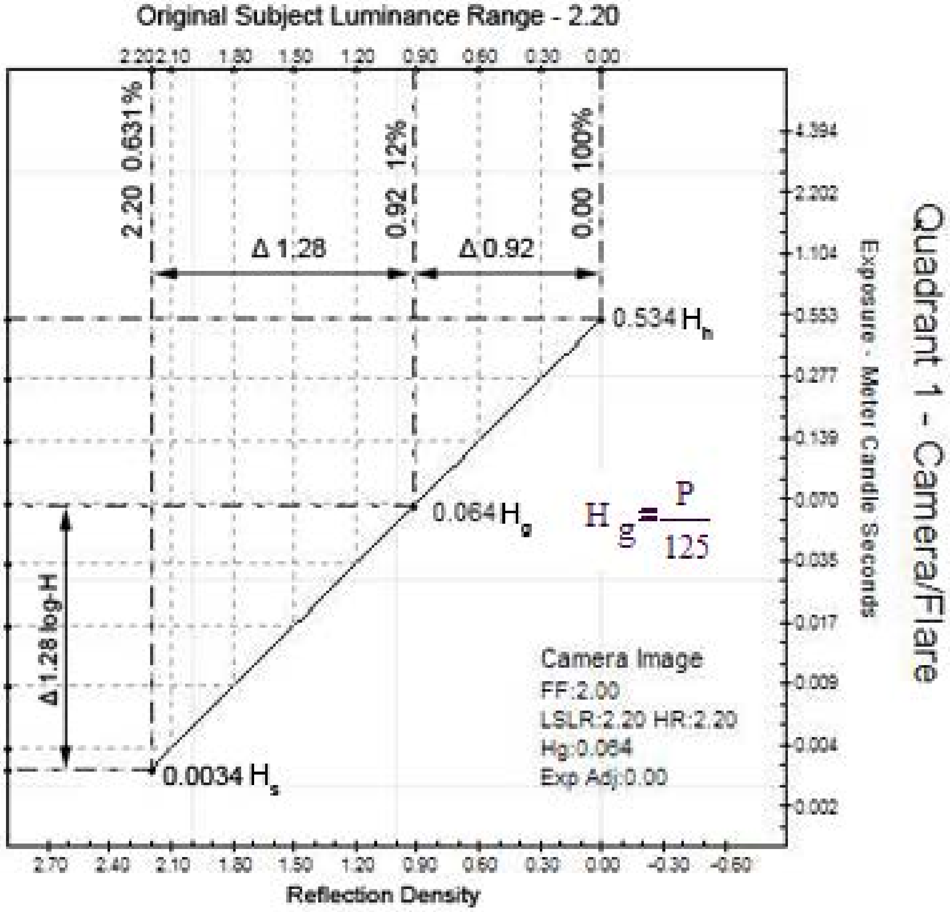
Where
H = Exposure at the film plane – in mcs or lux-sec
q = Exposure constant = 0.65
L = Luminance - in cd/m^2
A = Aperture number

$$\frac{0.65 \cdot 15.42 \cdot 10.76}{16^2} \cdot \frac{1}{125} = 0.0034 \qquad \frac{0.65 \cdot 297 \cdot 10.76}{16^2} \cdot \frac{1}{125} = 0.065 \qquad \frac{0.65 \cdot 2445 \cdot 10.76}{16^2} \cdot \frac{1}{125} = 0.534$$

$H_s = 0.0034$ mcs $\qquad$ $H_g = 0.065$ mcs $\qquad$ $H_h = 0.534$ mcs

The relationship between the original subject's luminance range and the resulting camera exposure values, H, can now be presented in a graphic form. The 2.2 log luminance range, in reflection density values, is indicated along the top of the graph. The three values of H are indicated along the camera image curve. The luminance range between L_s and L_g, L_g and L_h as well as the illuminance ranges between H_s and H_g are also shown.

Camera Image graph showing the relationship between the luminance range of the subject and the resulting camera exposure values, H, for a 125 speed film.

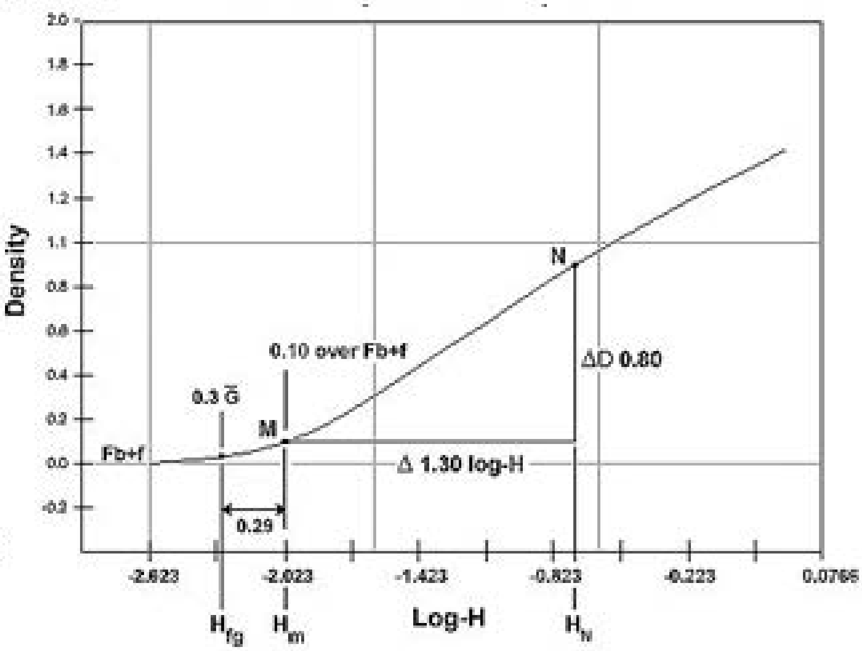


Part 5b is too big of a topic to do in a single installment. I'm going to stop here and the next installment will continue from where this left off.

The last installment defined the average luminance range as 2.2 logs. It showed how the constant P relates the material's film speed to the preferred exposure indicated by the meter and depicted the camera image in graphic form for a 125 speed film.

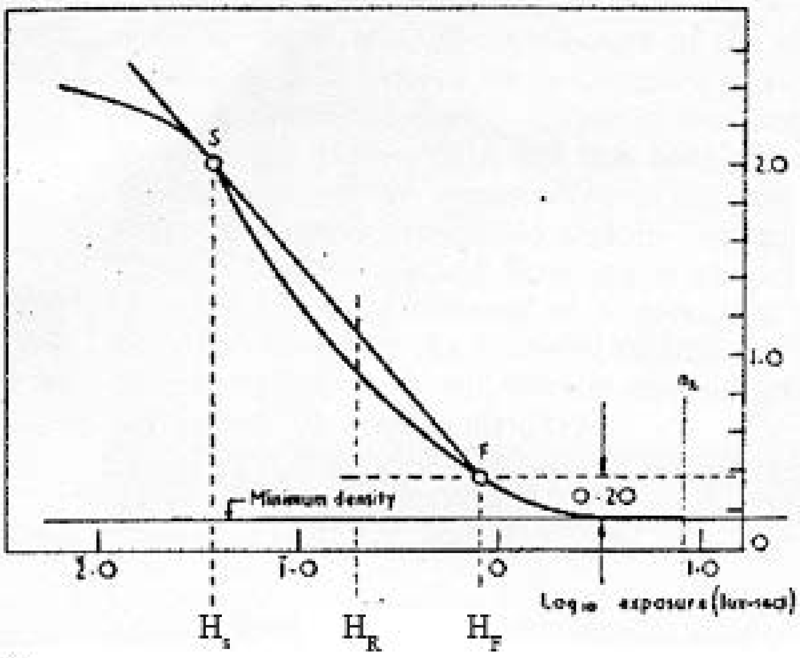
The next step is to define the relationship between the camera exposure and the sensitometric exposure or speed point in order to determine the placement of the camera exposure onto the film curve. While it has already been shown that this is done by multiplying the reciprocal of the film speed number with P = 8, it doesn't explain concept of the film speed number's function or its relationship with exposure placement.

The camera image's illuminance range as determined by the scene's luminance range needs to be placed on the film curve within some kind of context. The exposure requirements of the various photographic materials have been determined through testing which differ depending on the film type and purpose of use. Shadow exposure was found to be the principle factor in the perception of a quality photograph with black and white negative film and the quality of the midtone is used for color reversal film. Other specialty films, like aerial and microfilm, have their own requirements.



Black and white negative film speed is determined by the exposure, H_m, required to produce at a point of density of 0.10 above film base plus fog under specific contrast conditions. Color reversal film speed is the geometric mean exposure, H_R, between point, F, having a density 0.20 above minimum density and a maximum density point on the curve, S, tangential to F where the density doesn't exceed 2.0.

Even though speed is determined at different points on the film curve for different types of film all having different requirements, all must work with a single meter without having to change the calibration of the meter for each film type. What is not commonly known is that film speed and sensitometric exposure (speed point) are not necessarily the same thing. Sensitometric exposure is related to the point on the log-H where the speed is measured. The film speed number is connected to an actual value of exposure only through a constant associated with it.



There are two ways of thinking about film speed. Speed as property of a photographic emulsion and speed as a practical approach to have an index to enter into a meter. I don't believe the concepts are mutually exclusive. They simply address the two major problems involved in attempting to devise a rational speed number:

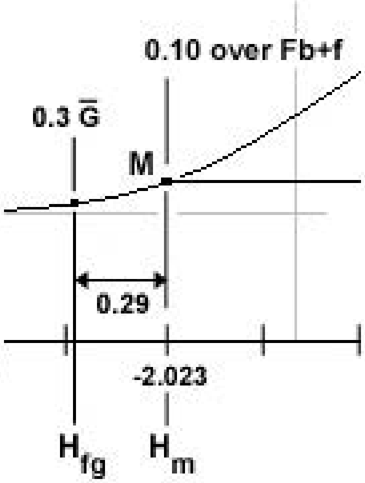
1. The definition of exposure
2. A criterion of excellence for the photographic image.

The speed point defines the characteristics of the film which produce the most consistent measurement, and the constant, whether as part of the standard or modified by the user, creates the desired index.

The concept of the speed point is for its placement to be in the region of the film curve that is the most critical for correct exposure determination and to be able to be determined within a methodology in an accurate repeatable manor that is applicable in the greatest number of conditions with the greatest number of emulsions. But this isn't necessarily where the critical exposure component is designed to fall.

With the fractional gradient method, the speed point was chosen because it represented the minimum gradient necessary for the negative to produce a quality photograph. As shadow reproduction was found to be one of the principle factors in producing a quality print, it would make sense to know the extent of the lower limits.

The factional gradient speed point falls approximately one stop to the left of the 0.10 fixed density speed point. Judging from its position alone, it should produce film speeds one stop faster; however, speeds derived from the fractional gradient method actually were around one stop slower. The reason for this is the log-H exposure is divided into a constant. This constant is considered arbitrary in that it is chosen not for an inherent reason, but like the exposure constant P, it comes from psychophysical and field testing and is chosen to optimize the exposure placement for a given photographic material.



Fractional Gradient Speed

$$\text{Speed}_{FG} = \frac{.25}{H_{fg}} \qquad \frac{.25}{.0032} = 78$$

ISO Fixed Density Speed

$$\text{Speed} = \frac{0.8}{H_m} \qquad \frac{.8}{.0064} = 125$$

The film speed constant also makes it possible to make adjustments to the film speed without having to change the proven methodology or making a change to the exposure meter. Color reversal film used to have a speed constant of 8. Sometime in the 70s it was changed to 10. This made transparencies one third stop faster.

$$\frac{8}{.064} = 125 \qquad \frac{10}{.064} = 156$$

Black and white film speeds effectively doubled in 1960. The reason isn't as easy to illustrate as the color reversal change because the film speed change was accompanied by a change in the speed determination methodology. The reason for the adjustment was to eliminate a safety factor that was no longer necessary because of better lenses and lens coating, more accurate exposure meters, and the increased use of smaller formats.

According to C.N. Nelson, the speed change could have been accomplished by changing the speed constant of the fractional gradient method from 0.25 to 0.40. After all, the fractional gradient method was proven to be the most accurate method with the greatest variety of emulsions under the largest range of conditions. But in general practice, the fractional gradient method was prone to testing errors. ANSI wanted to create an international speed standard and knew that the Europeans wouldn't adopt the fractional gradient method. They found that when the DIN's fixed density method of 0.10 above film base plus fog method was used under certain contrast parameters, the speed produced using the fixed density method was the same as what would have been produced by the fractional gradient method. The contrast parameters are critical, because without it, the fix density method doesn't have as high a level of consistency of exposure as the fractional gradient method. They changed the methodology of speed determination to 0.10 not because it there was any intrinsic significance to a density of 0.10, but because it was easier find and therefore a more repeatable method.

We already know that 0.10 doesn't represent the minimum useful density because the fractional gradient method's speed point basically represents that and it is located almost one full stop to the left. Again, it's used basically because it is easy to find. The USSR's old GOST method used a fixed point at a density of 0.20. Obviously this doesn't represent the minimum useful density. It should be a surprise that both represent 1/3 stop increments. If the speed point was to use a minimum useful density point, it probably won't work out to be such a nice round number.

Additionally, the film speed number derived from the ISO $0.8/H_m$ equation doesn't represent the value that should be determined at that precise point. For that to happen, the equation would have to be 1/Hm. Much like the factional gradient method, this is an example of how the speed point is where the speed is determined, but the constant adjusts what the speed number is which when plugged into the exposure meter determines where the exposure will fall on the curve. In this case, it's a one third shift toward a slower film speed. But that doesn't necessarily mean that there is a one third stop safety factor only that from the 0.10 fixed density point, the film speed exposure number needed to be adjusted in order for the exposure for an average luminance scene to fall on the curve where it will produce a quality print in accordance with psychophysical testing.

In order to find the relationship between the sensitometric measure of exposure, Hm, and the photographic exposure requirement, Hg, the ratio between the two must be determined, k_1 for b&w. The values are for 125 speed but the results are universal to all speeds.

$$k_1 = \frac{H_g}{H_m} \qquad k_1 = \frac{.064}{.0064} \qquad \frac{.064}{.0064} = 10 \qquad k_1 = 10$$

The difference between the photographic exposure and the sensitometric measurement is 10x, or 1.0 log-H, or 3 1/3 stops.

With k and the speed constant n, it can be shown the relationship "between the parameters involved in the determination of the exposure required for an average scene and also provide the basis upon which calibration techniques of exposure devices are decided," D. Connelly, Calibration Levels of Films and Exposure Devices.

$$H_m \cdot S = \frac{H_g}{k_1} \cdot S = \frac{E_g \cdot t \cdot S}{k_1} = \frac{q \cdot L_g \cdot t \cdot S}{A^2 \cdot k_1} = n$$

n using speed point exposure and film speed number

$$n = H_m \cdot S \qquad .0064 \cdot 125 = 0.8$$

n using the classic exposure equation combined with k1

$$n = \frac{q \cdot L_g \cdot t \cdot S}{A^2 \cdot k_1} \qquad \frac{.65 \cdot 297 \cdot 10.76 \cdot \frac{1}{125} \cdot 125}{16^2 \cdot 10} = 0.811$$

The following equation comparison illustrates relationship of film speed, camera exposure, and the exposure meter exposure.

$$H_g \cdot S = \frac{q \cdot L_g \cdot t \cdot S}{A^2} = n \cdot k_1 = P$$

Combined with the exposure meter calibration and the relationship can be reduced down to the constants as long as p = 1.

$$K = \frac{P}{q} \qquad \frac{8.11}{.65} = 12.5 \qquad \frac{\frac{8.11}{.65}}{10.76} = 1.16$$

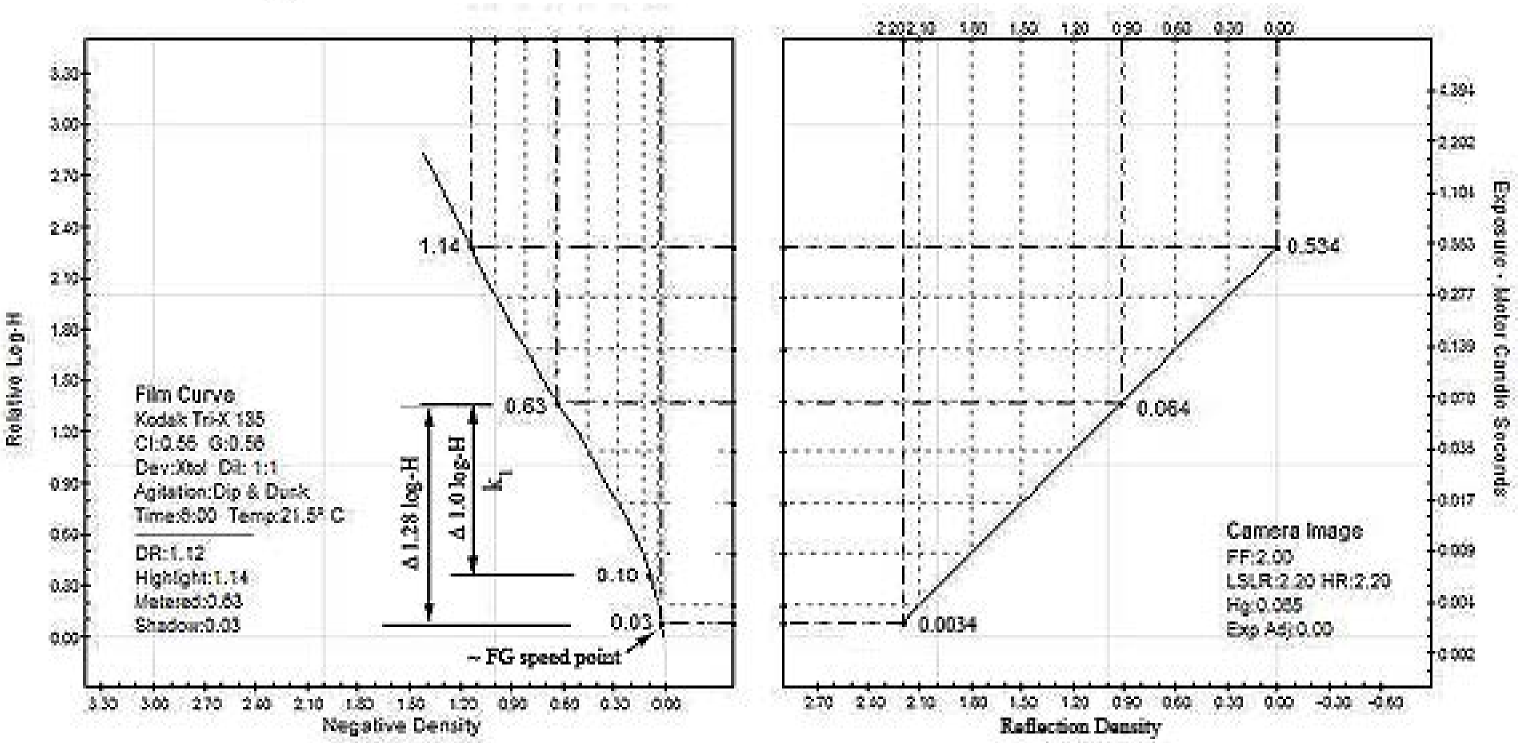
By using this equation, Hg for any value of K can be easily determined. For instance K = 1.30/14 for a 125 speed film.

$$P = K \cdot q \quad (1.30 \cdot 10.76) \cdot .65 = 9.1 \qquad \frac{9.1}{125} = 0.073 \quad H_g = 0.073 \text{ mcs}$$

For K = 1.30, k1 becomes 11.25.

$$\frac{H_g}{H_m} \qquad \frac{.072}{.0064} = 11.25$$

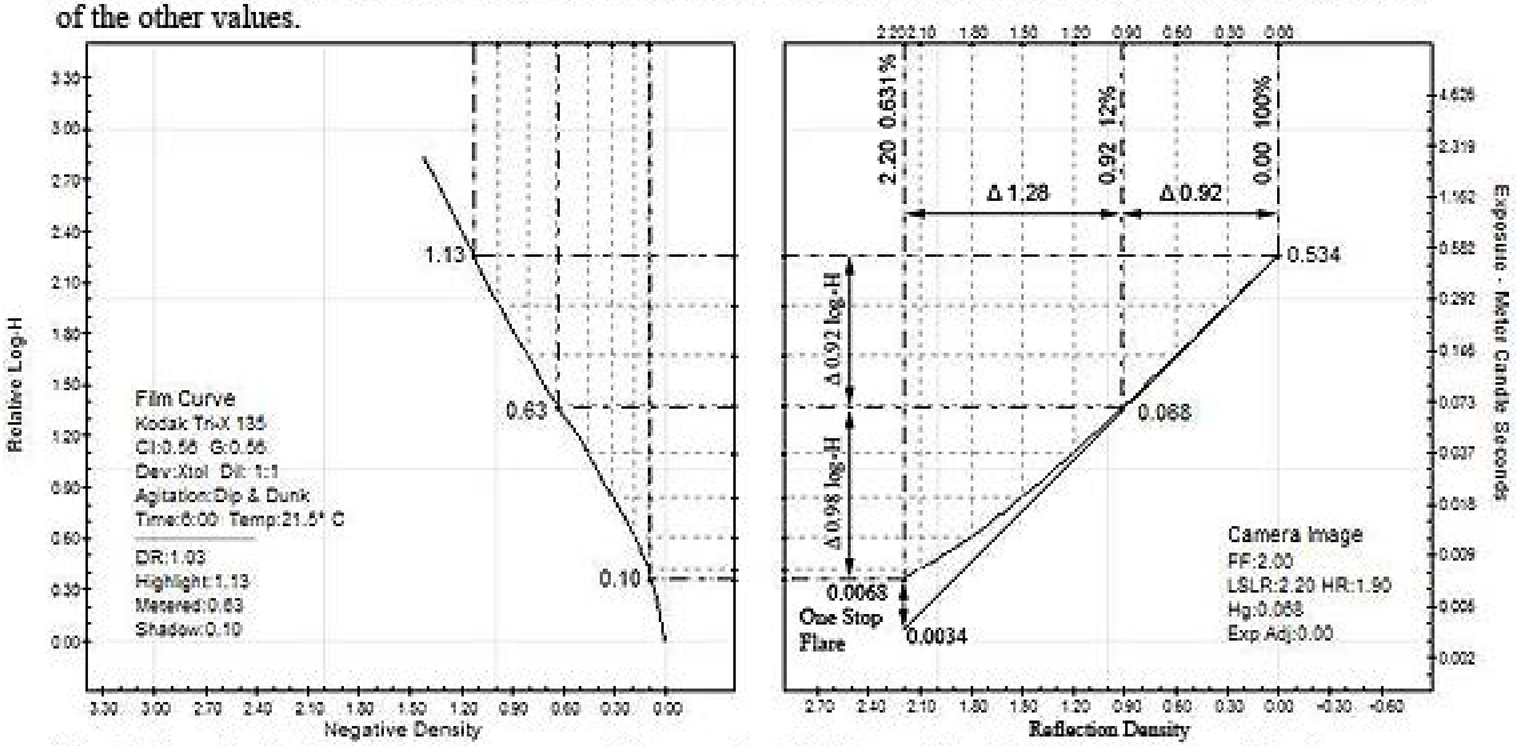
Now we can project the camera image exposure for the average scene luminance range of 2.20 onto the film curve based on P, n, and k1.



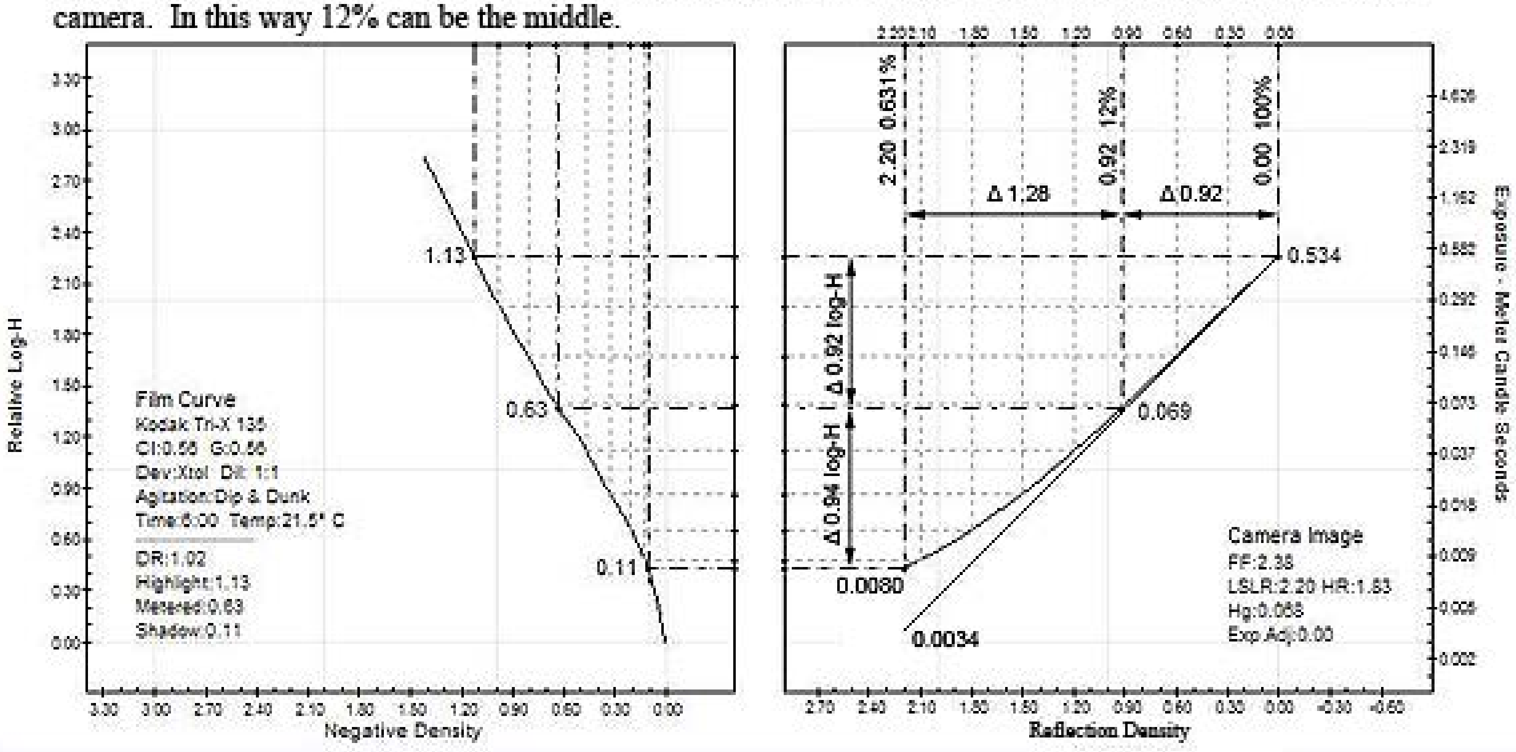
It is obvious from the example that the shadow exposure doesn't correspond with the speed point, but remember the measurement of the sensitometric exposure, speed point, and the camera exposure aren't the same thing. Also remember that n and P are derived from psychophysical testing which takes into account field conditions. One additional factor remains needs to be added to the exposure equation in order to make a full accounting of those conditions. Incorporated in the camera image along with the exposure values from the scene's luminance range is veiling flare. While flare adds to the over all exposure, its influence is mostly in the shadow area. A one stop flare factor means that the shadow exposure has doubled. In the example, that would increase the shadow exposure from 0.0034 to 0.0068. This same amount of exposure is applied to every point in the camera image, but an increase of 0.0034 doesn't make much of a impact on the highlight exposure of 0.534. For the most part, film speed number doesn't factor in flare directly. It is concerned with the sensitometric exposure, but n and k_1 take flare into account in determining the exposure placement.

What flare does is to change the ratio of the luminance range to the illuminance range within the camera image. A one stop flare factor will take the average log 2.20 luminance range and reduce it to an effective 1.90 luminance range in the camera. This reduces the log-H range between H_g and the shadow exposure and changes the location of its placement on the film curve.

Average flare is from 1 to 1 1/3 stops. One stop is frequently used with exposure theory, 1 ¼ stop is used with large format cameras, and 1 1/3 stops is generally applied to 35mm and sometimes medium format. For the sake of clarity, I'm going to be using one stop for the standard exposure model, but I will also illustrate one of the other values.



Flare brings the shadow exposure up around the speed point. I consider this the standard model of exposure because it shows how everything is supposed to work when all the conditions are average. But the value for flare is really the lowest average value. The example below shows what happens with 1 ¼ stop flare As the example shows, in most cases the shadow exposure will fall slightly to the right of the speed point. Another interesting observation can be made from the example. The illuminance range above and below H_g is almost equal. This suggests that the idea of middle gray comes from the way the luminance range balances in the camera. In this way 12% can be the middle.



In the last installment I illustrated the part flare plays in exposure and how the assumption of flare factors into k_1 and the placement of exposure. The piece was running long and I wasn't able to explain how flare is calculated and incorporated into the exposure equation.

Camera image equation:

$$H = \left(\frac{q \cdot L}{A^2} \cdot t\right) + H_f$$

Where
H = Exposure at the film plane – in mcs or lux-sec
q = Exposure constant = 0.65
L = Luminance - in cd/m²
A = Aperture number
t = Shutter speed
H_f = Flare - in mcs or lux-sec

There are a number of ways to calculate flare, but I've found this method works well:

$$H_f = \left(H_s \cdot 2^F\right) - H_s$$

Where:
H_s = shadow exposure – in mcs or lux-sec
F = flare factor in stops

I like to calculate L using the following equation which incorporates the reflection density of the subject and the illuminance.

$$L = \frac{\left(E \cdot \frac{1}{10^{RD}}\right) \cdot 10.76}{\pi}$$

To determine Hs, we will assume the average value for luminance range, 2.20, 100% reflectance for the highlight and 7680 cd/ft² for the illuminance. t is the reciprocal of the film speed, which will be 125.

$$H_s = \frac{\frac{.65 \cdot \left(7680 \cdot \frac{1}{10^{2.2}} \cdot 10.76\right)}{\pi}}{16^2} \cdot \frac{1}{125}$$

$$H_s = 0.0034 \text{ mcs}$$

For a one stop flare factor H_f would be:

$$\left(0.0034 \cdot 2^1\right) - 0.0034 = 0.0034 \text{ mcs}$$

For a one and 1/3 stop flare factor H_f would be:

$$\left(0.0034 \cdot 2^{1.33}\right) - 0.0034 = 0.0051 \text{ mcs}$$

The example below is applying the exposure equation with one stop flare and without flare for the range from RD 0.00 to 2.20 at log 0.10 intervals. This is how the camera image curve is calculated in quadrant 1 of my four quadrant program.

R	RD	H	$H + H_f$
100.0	0	0.5343	0.5377
79.4	0.10	0.4244	0.4278
63.1	0.20	0.3371	0.3405
50.1	0.30	0.2678	0.2712
39.8	0.40	0.2127	0.2161
31.6	0.50	0.1690	0.1724
25.1	0.60	0.1342	0.1376
20.0	0.70	0.1066	0.1100
15.8	0.80	0.0847	0.0881
12.6	0.90	0.0673	0.0707
10.0	1.00	0.0534	0.0568
7.9	1.10	0.0424	0.0458
6.3	1.20	0.0337	0.0371
5.0	1.30	0.0268	0.0302
4.0	1.40	0.0213	0.0247
3.2	1.50	0.0169	0.0203
2.5	1.60	0.0134	0.0168
2.0	1.70	0.0107	0.0141
1.6	1.80	0.0085	0.0119
1.3	1.90	0.0067	0.0101
1.0	2.00	0.0053	0.0087
0.8	2.10	0.0042	0.0076
0.6	2.20	0.0034	0.0068

Exposure at speed point for 125 speed film.

$$\frac{0.8}{125} = 0.0064 \text{ mcs}$$