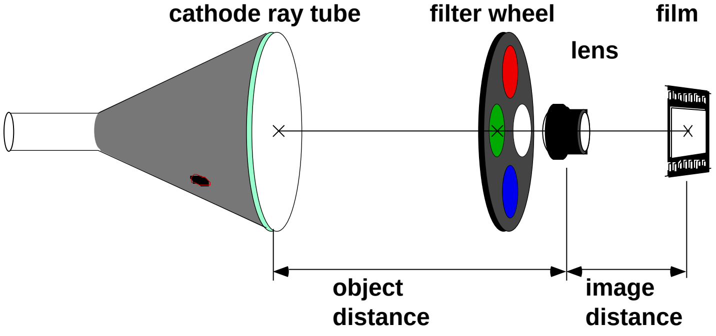


Typical CRT film recorder optical path. The four elements illustrated here are present in some form in all film recording equipment. A diverse range of technology has been applied to the problem of recording images on film; CRTs are a dominant choice due to their relatively low cost. The demands on the writing equipment are high because the media, silver-based film, is so capable and its performance continues to improve.

Light sources used in film recorders:
- CRTs
- xenon lamps
- lasers

Light source requirements:
- contain energy at long, medium, and short wavelengths
- bright enough for useful exposure times
- able to be regulated and modulated

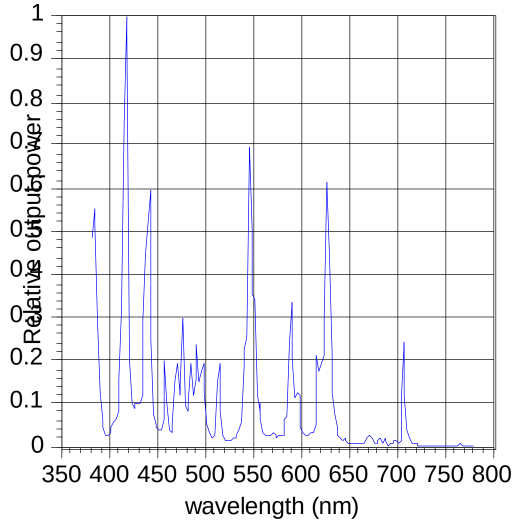
Film exposure sources and their requirements.

Pulse width exposure control
- linear response:
  $e = \alpha v$

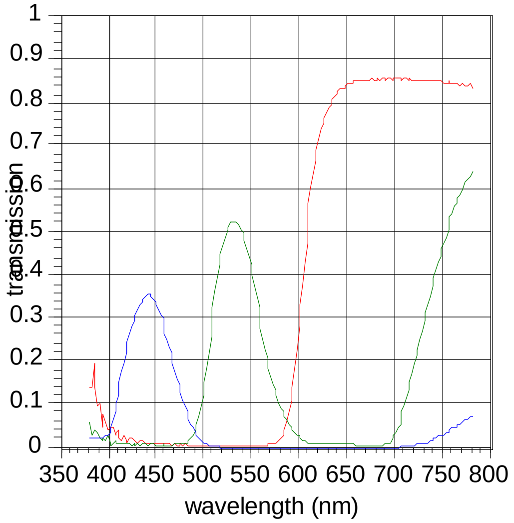
Intensity control
- crossed polarizers
  $e = \alpha \sin^2 v$
- CRT grid drive:
  $e = \alpha v^\gamma$
- acousto optic modulator:
  $e = \alpha v$

Modulating the light. Different sources utilize different methods for controlling pixel intensities. Each has its characteristic transfer function from the control signal v to the light energy delivered to the film.

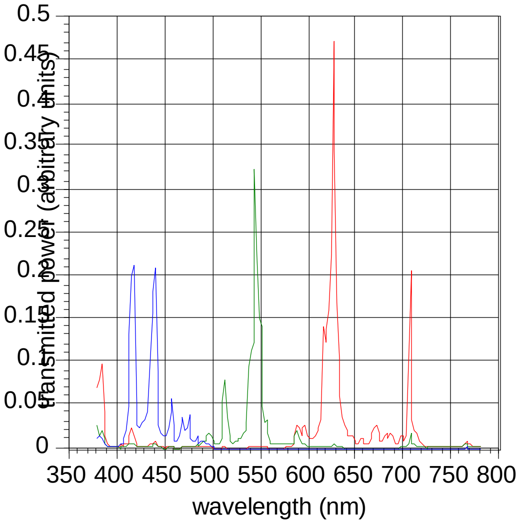
Light source spectrum Each light source has its own distinct spectral power distribution. Sources which have energy in each of the long, medium, and short wavelength regions of the spectrum can be perceived as "white" even though not all wavelengths are present. This is the spectrum of a phosphor used in CRT film recording.

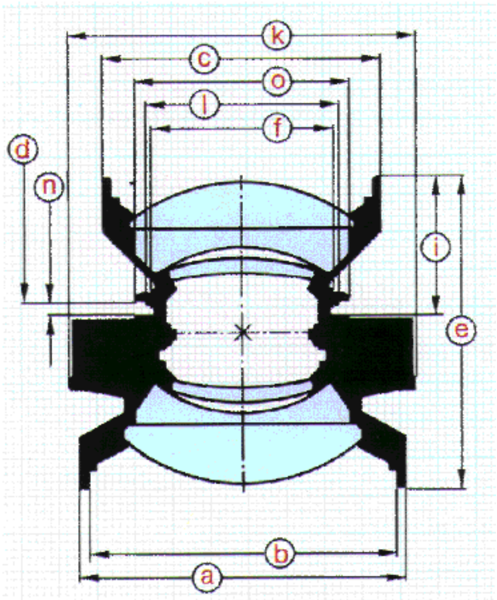


Color separation filters. In order to control the energy delivered from each band, separate exposures are made, each from an isolated part of the spectrum. To block the unwanted part of the spectrum, color filters are placed between the source and the film.

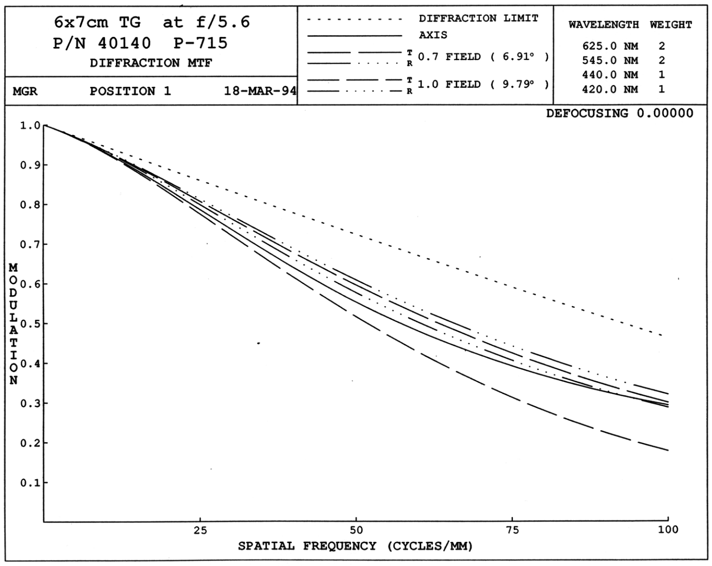


Filtered CRT spectrum. The degree of color saturation that can be achieved depends in part on how pure the three wavelength bands of the exposure can be made. The plot here shows the net energy in each band of the filtered phosphor spectrum. Narrowband sources provide for a wide color gamut, but the tradeoff is in obtaining enough energy to make the exposure in a reasonable time.

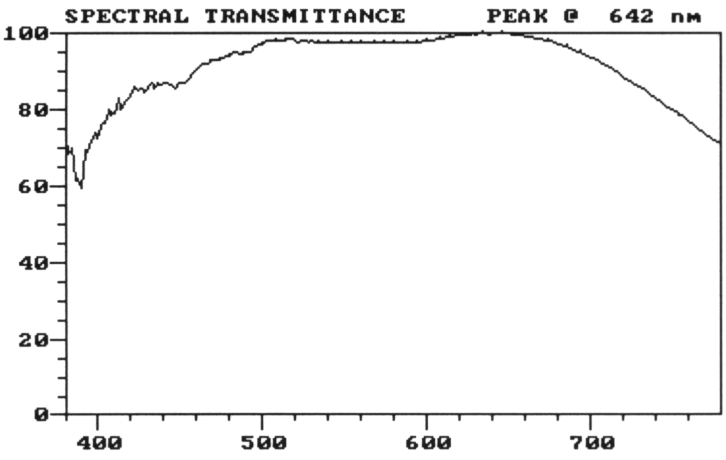




Optics. The exact optics configuration is highly dependent on the exposure technology, but it is a critical component in the system. In general, modern lens elements are quite clear across the spectrum and do not influence color strongly. Each surface of a lens element introduces reflections however, and if many elements are involved they will add up and result in *flare*. Anti-reflection coatings are mandatory, but even so, it is difficult to obtain less than 1% flare in a compound lens design.



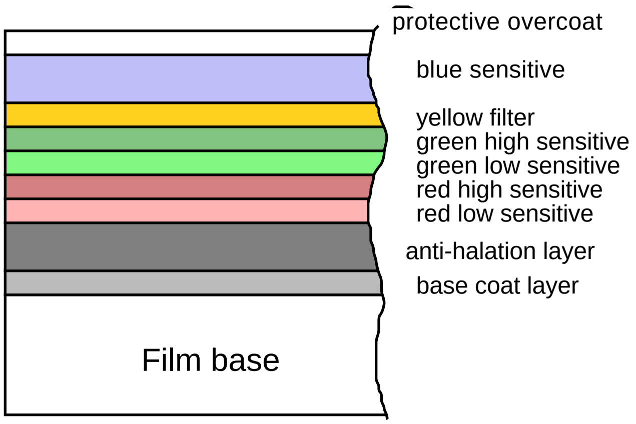
Modulation transfer function. The exact glass type, surface design, and alignment of the lens elements, all contribute to the overall sharpness of the resulting image. The MTF performance curve embodies how well a lens can reconstruct spatial frequencies at its image plane. A figure of merit for a lens is the frequency which can be imaged at a 50% contrast level, the spatial bandwidth of the lens.



Lens transmission and scattering. Most lens elements are quite clear across the visual spectrum. The anti-reflection coatings on the other hand, tend to favor certain wavelengths over others, and many glass types start to exhibit scattering at the blue end of the spectrum. The result of these effects is to introduce a slight tint to the flare associated with the lens.

Film construction. Modern photographic film is a complex material. The emulsion layers in color film are all sensitive to blue. To make green-only and red-only sensitive layers, a yellow filter is placed in front (but below the blue-sensitive layer), blocking the blue light from reaching them.

Each color sensitive layer may actually comprise several layers, each with a particular response range to extend the film's latitude. Additional layers are needed to control halation and to aid in the manufacturing process.



Density definition. As one exposes film to more light, after development it becomes darker, more opaque, less transmissive. The units of density are easily derived from transmission, though such measurements are subject to variables of angles, scattering, and spectral weighting. The exact methods used to measure transmission (or reflection) are the subject of a number of standards, which are implemented by commercial densitometers.

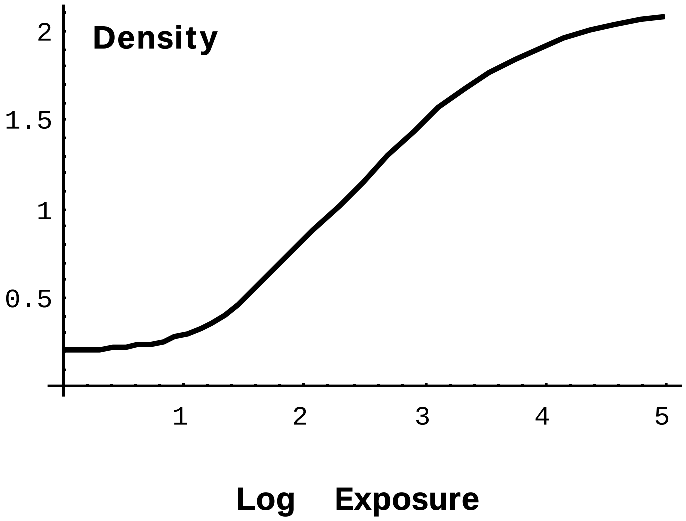
"Density" is the logarithm of "opacity".

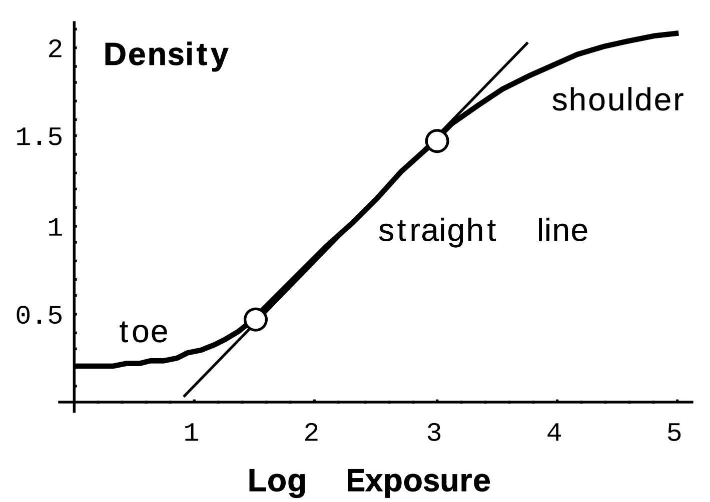
Opacity is the reciprocal of transmission:

$$o = 1/t$$

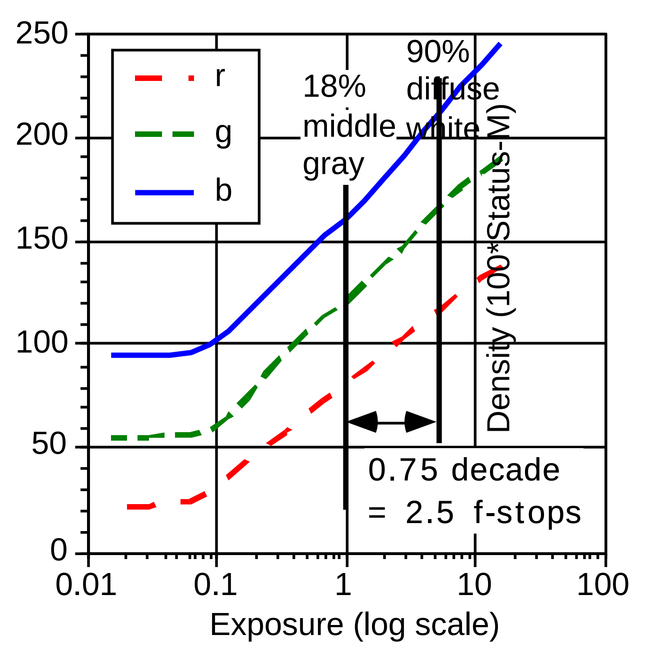
$$D = \log o = \log 1/t = -\log t$$

Basic film response, the HD curve. The fundamental behavior of film is based on the interaction between photons and silver ions in the film. The statistics of the spatial distribution of the developed silver grains results in this characteristic curve shape when optical density is plotted against log exposure. Such curves are called DlogE curves, characteristic curves, or HD curves, after Hurter and Driffield, early photographic scientists who pioneered this method of describing film behavior.



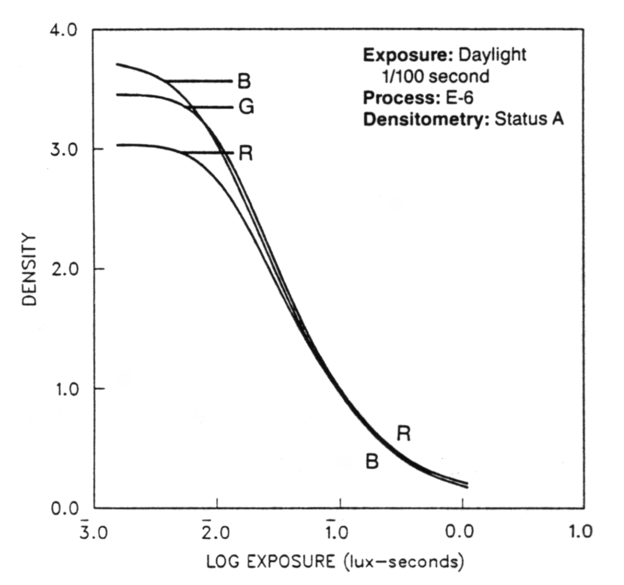


Key features of the characteristic curve. The general appearance of characteristic curves are quite similar. Each starts out at the film base density and then as exposure increases, the density starts to build up. The density response then enters a region where it increases proportionally to the log exposure. The onset and the slope of this straight line region establish the *speed* and *contrast* of the film. Eventually, the developed metallic silver approaches the total amount available in the emulsion and the response saturates.



Color film curves. Color film has the same general behavior, but in three separate response curves, associated with the three bands of the spectrum. They are offset from each other because of *colored couplers* (mask layers) that help compensate for unwanted dye absorptions.

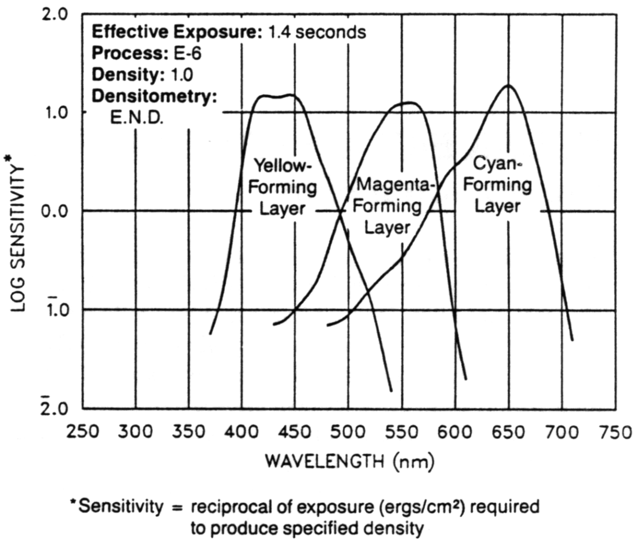
Typically, only the toe and part of the straight line portions of the response curve are used. Overexposure simply translates the scene information up the curve, providing *exposure latitude*. The excess density is compensated by overexposing during the printing step. The low contrast (low slope) of the negative is also compensated by the slope of the print paper response.



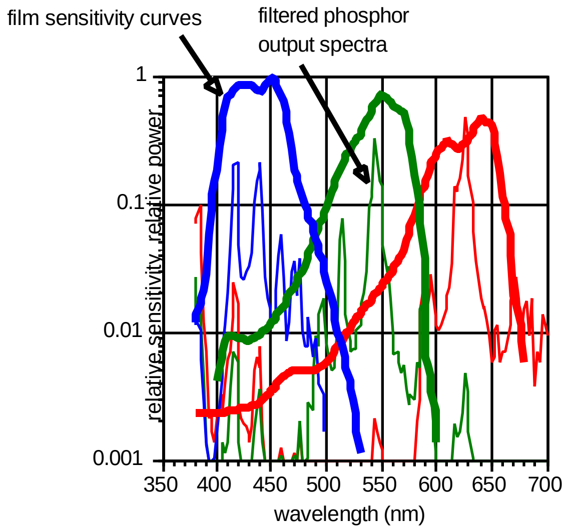
Color reversal film. A special developing process can convert the normal negative response of silver halide film to a positive. It involves developing and removing the initially exposed silver, and then converting the remaining silver halide to metallic (opaque) form. The image ends up reversed from its normally developed state, and so is called a color reversal process.

The film contains the positive image which is viewed directly or projected. Because of this, the exposure, tone response and color balance must be very tightly controlled; no subsequent printing step is available for compensation.

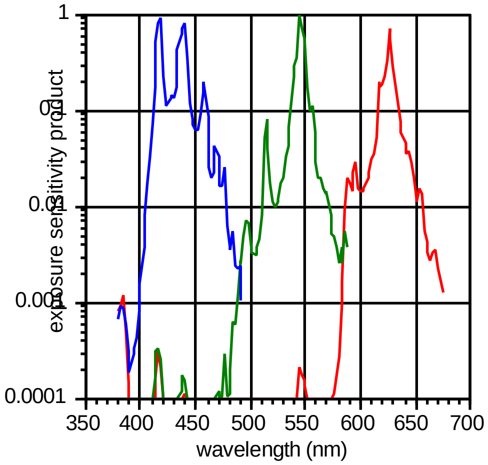
Exposure and sensitivity. *Exposure* is measured as a light intensity-time product such as "lux-seconds". *Sensitivity* is the reciprocal of the exposure needed to reach a specified target density.

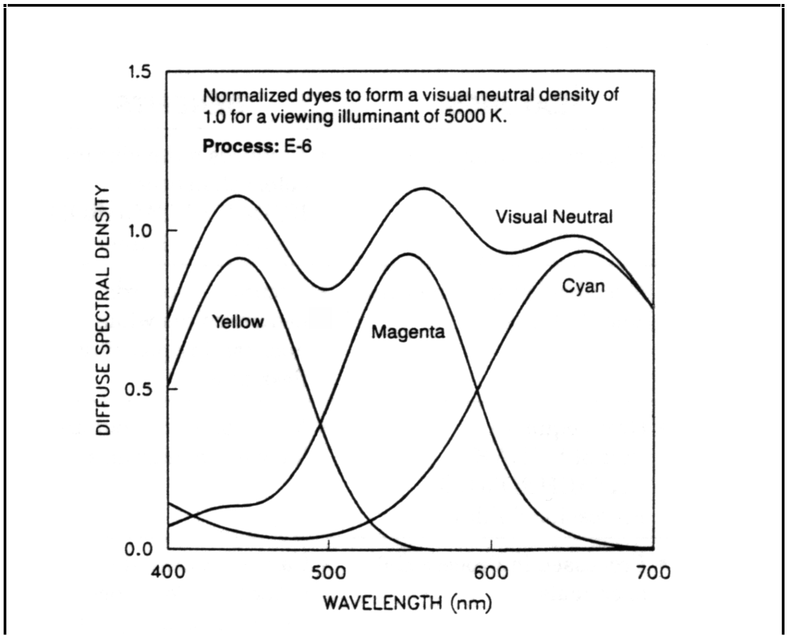


Sensitivity relative to the exposure spectrum. Here are the sensitivity curves superposed on the spectral components of the color separated CRT phosphor. It is desirable to have the exposure energy in each band match the corresponding sensitivity function without influencing the other layers of the film.

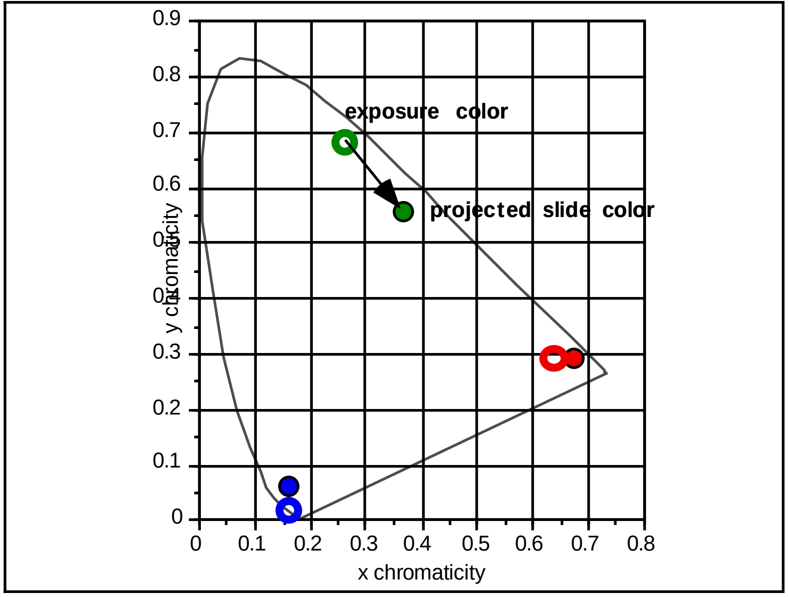


Sensitivity weighted exposure spectrum. The product of the sensitivity curves with the exposure spectra give us an idea of the relative amounts of energy being delivered to each film layer, and also the amount of crosstalk (unwanted exposure) to the other layers. The better the isolation between channels, the better the saturation of the resulting film color, and the larger the color gamut of the system. It is seen here that the line spectrum of the phosphor coupled with the color separation filter pass and stopbands and the sensitivity curves of the film results in very good, but not perfect, separation.





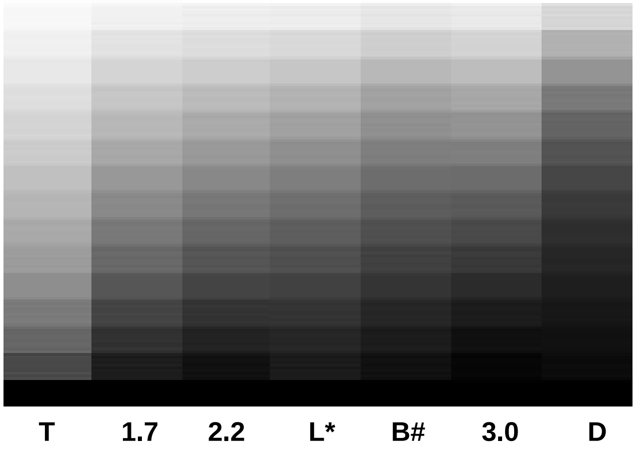
Dye absorption spectra. No matter how pure the exposure however, the resulting film image is the superposition of three dye spectra. The spectral bandwidth and separation of these dyes constrain the saturation and brightness of the final picture. In this plot the individual dye absorption curves are shown. Each *blocks* a portion of the spectrum and is transmissive elsewhere (though not perfectly so). The net result is a spectrum which is blocked partially everywhere. The relative concentrations to make a visual match to a uniform 10% transmission (neutral density 1.0) across the full spectrum are shown.



Colorimetry of digitally exposed film. The locations of the projected film primaries are shown on this chromaticity chart, compared to the color of the light that made the exposure. It can be seen that green and blue desaturate, while red actually increases in saturation. The final colors seen in the projected slide depend on the final dye concentrations in the film, and the spectrum of the projector bulb, a light source which has a strong red component.

Common tonal scales used in digital imaging

File format	ext	implicit scale
SGI	.rgb	gamma 1.7
Targa	.tga	unspec, 2.2
Tagged Image File	.tif	various
Cineon, 10-bit	.cin	printing den
Cineon 8-bit	.cin	printing den
Cineon 8-bit	.rgb	linear lum
D1		gamma 2.2
Macintosh		gamma 1.8



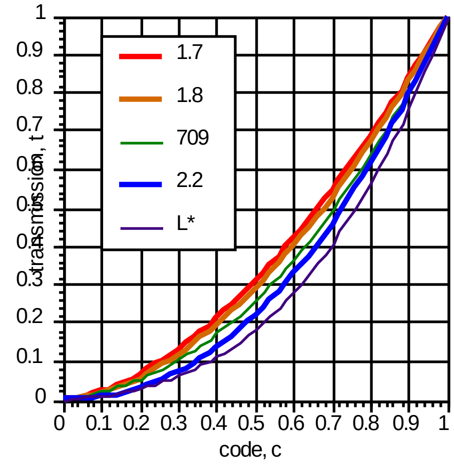
Simple power laws:

$$t(c) = t_{min} + (t_{max} - t_{min})c^{\gamma}; \quad 0 \le c \le 1$$

$\gamma = 1.7$ for SGI workstation monitors

$\gamma = 1.8$ for Macintosh monitors

$\gamma = 2.2$ for calibrated video monitors



Offset power laws:

L*:

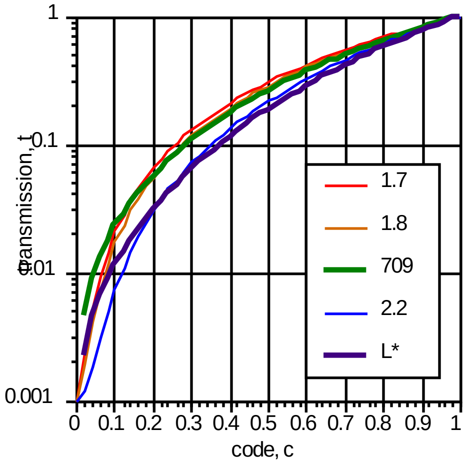
$$t = t_{\max} \frac{c}{9.033}, \qquad c \le 0.08$$

$$t = t_{\max} \left(\frac{c + 0.16}{1.16} \right)^3, \qquad 0.08 < c$$

PhotoCD, CCIR 709:

$$t = t_{\max} \frac{c}{4.5}, \qquad c \le 0.08$$

$$t = t_{\max} \left(\frac{c + 0.099}{1.099} \right)^{\frac{1}{0.45}}, \quad 0.08 < c$$



Cineon 10-bit printing density:

$D(c) = 0.002c \qquad 0 \le c < 1024$

Cineon 8-bit printing density:

$D(c) = 0.008c \qquad 0 \le c < 256$

Cineon 8-bit linear luminance:

$t(c) = t_{max} * c/255 \qquad 0 \le c < 256$

Cineon tonal scales. There are several file formats that are used by the Cineon system to hold image data. The original scale used 10 bits to encode the equivalent printing density of the negative. Each digital count is worth 0.002D giving an enormous dynamic range of 2.048D (on the negative). Other scales have come into use: an 8-bit scaled version of density (0.008D/count), and an 8-bit linear luminance scale.

Other influences on film appearance:

viewing environment
  - normal (print)
  - dim surround (CRT)
  - dark surround (projected images)

flare

halation

grain