Oscilloscope Camera Concepts

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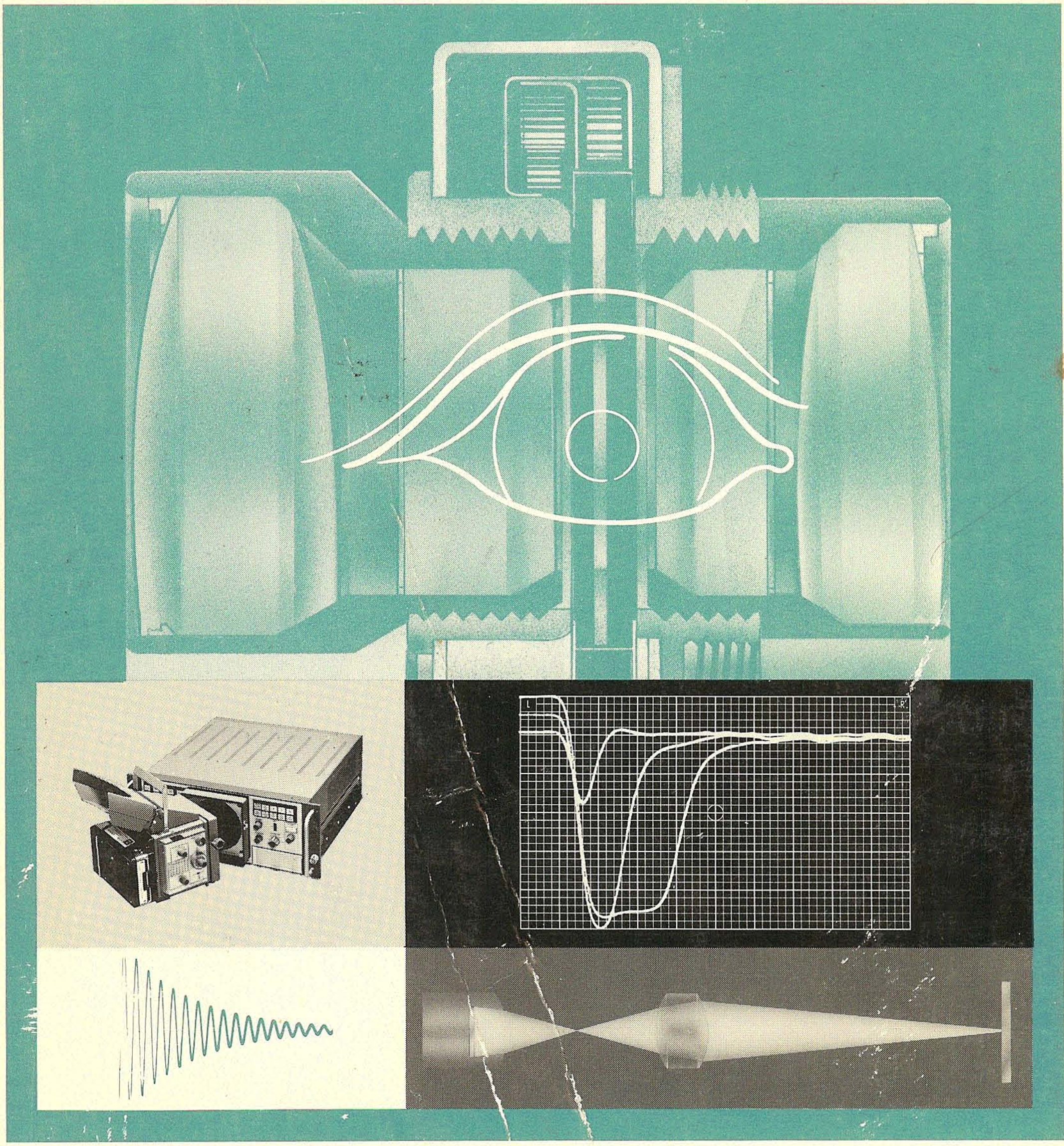

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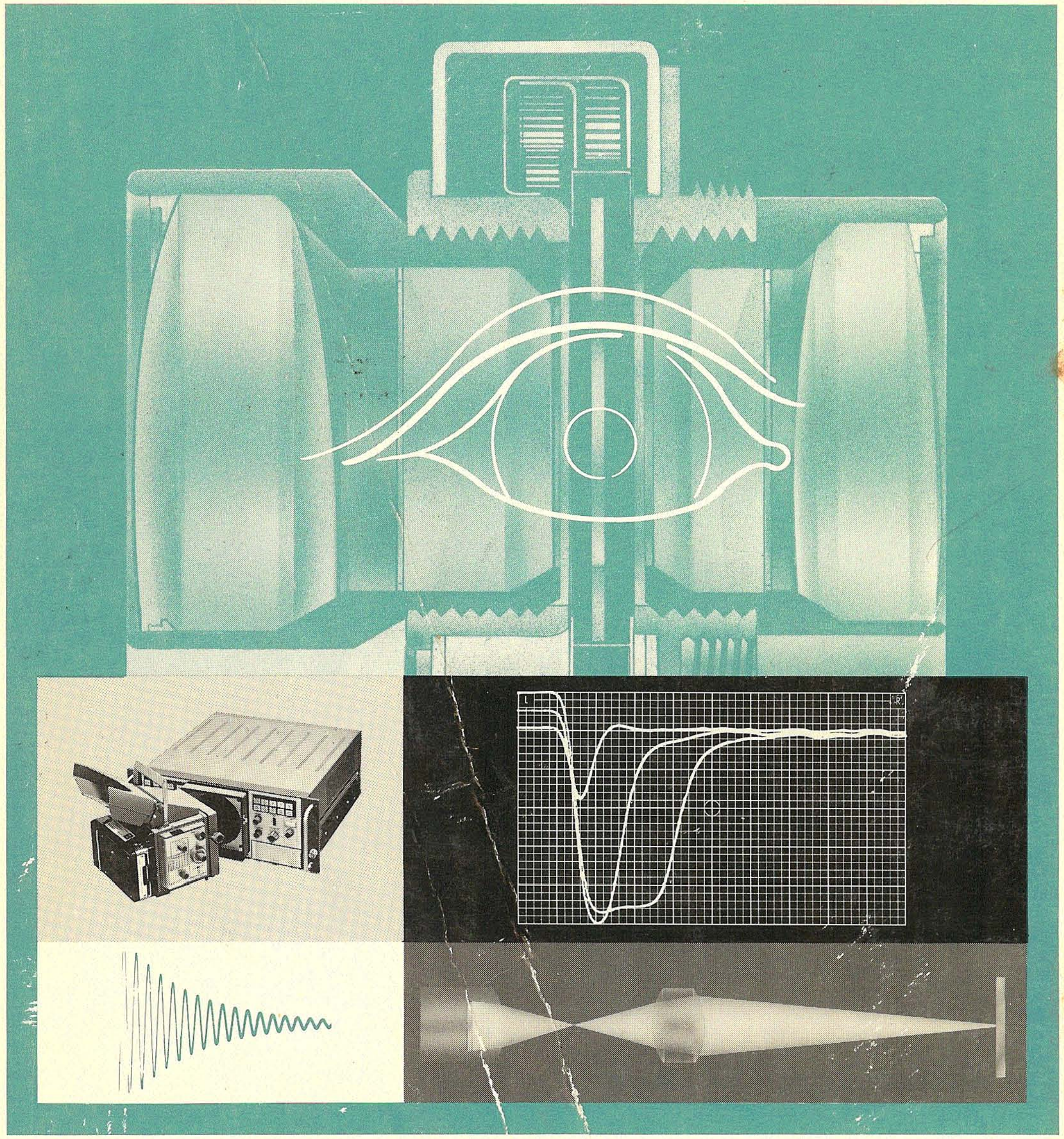

OSCILLOSCOPE CAMERA CONCEPTS

TEKTRONIX, INC.

OSCILLOSCOPE CAMERA CONCEPTS

BY

WILL MARSH

Significant Contributions

by

MAURICE J. MERRICK

BEN A. BUISMAN

CIRCUIT CONCEPTS

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CONTENTS

SYMBOLS AND TERMS

a	acceleration; loss factor
A	area; aperture stop; amplitude
A	ampere
B	luminance (power per unit area)
c	curvature; diameter of circle of confusion
c	speed of light
d	diameter, thickness, distance
D	density; lens power (diopters); diameter
e	charge on electron
E_e	illuminance (power per unit area)
E_x	exposure (energy per unit area)
f	frequency; focal length
fc	footcandle
fl	footlambert
F	force; back focal length
cd	candela (candle)
h	height; Planck constant ($\approx 6.63 \times 10^{-34}$ J · s)
H	principal plane
I	current; luminous intensity
J	energy per unit area
J	joule
k	correction factor
K	constant defined for any equation
l	length
$\log_n$	common logarithm to base n
L	luminance (power per unit area)
k	kilo
lm	lumen
m	mass; modulation
M	luminous exitance; modulation; photographic magnification

n	index of refraction; arbitrary number
N	noise power
o	opacity; object plane
P	power
q	electric charge
Q	radiant (luminous) energy
R	resistance
r	radius
S	surface area, focal length
S_x	ASA film speed
t	time
t_r	risetime
T	temperature; period; transmission
u	object distance
v	velocity; image distance
V	voltage; Abbe number
V	volt
W	energy, kinetic
W	watt
WD	working distance
x	distance; horizontal coordinate
y	distance; vertical coordinate
z	depth coordinate
α	angle, lens half-angle
β	angle
γ	angle; gamma – contrast ratio
θ	angle
ν	frequency
ρ	reflection factor
ϕ	angle
Φ	radiant (luminous) flux
ω	solid angle

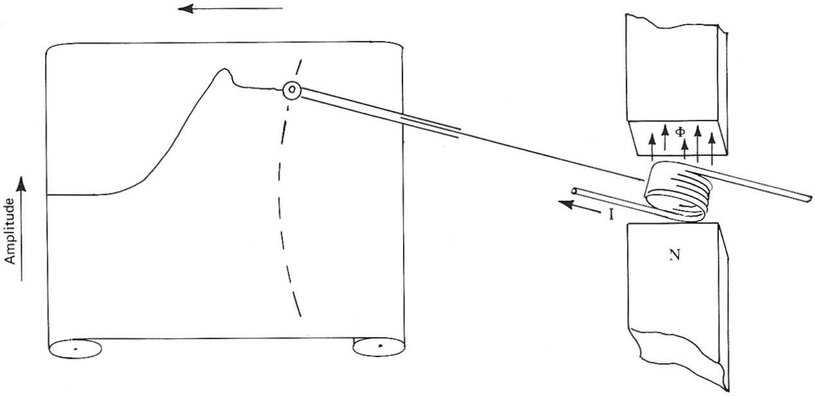

Fig. 1-1. Fundamental analog recorder.

1

INTRODUCTION

Many electronic technicians who are very competent in circuitry find themselves handicapped when they encounter an oscilloscope camera system.

A great volume of material has been written about all the technical elements of oscilloscope photography, but most of it must be found in different parts of the library. Here we have tried to assemble enough information about each area of technology to provide adequate understanding, without burdening the reader with more than he needs to know. We have tried to emphasize that material which appears to be not well understood by many people who need it.

measuring devices

The commonly known measuring devices, such as electric meters, thermometers and barometers provide a *steady-state* measurement that does not change as the reading is taken. When the same kind of measurement is taken with a recording instrument, all the variations are indicated on the chart, which is actually a graph of the variation of amplitude against time. When the amplitude changes occur in less than .01 seconds, it becomes increasingly difficult to design a meter movement that will respond quickly enough to record accurately the excursions of the amplitude.

oscilloscope

The cathode-ray beam has almost zero mass, and provides a meter movement that responds in nanoseconds rather than milliseconds. In addition, the beam can be made to move horizontally as well as vertically, providing both coordinates for a graph. If a repetitive event is being investigated, the horizontal excursion of the trace can be synchronized with the signal (better, triggered by the signal) so the display remains stationary.

trace recording

The display can then be physically measured, traced on paper directly from the film, or photographed. These results are relatively easy to accomplish, depending on the characteristics of the signals being displayed.

single event recording

When the event occurs only once, a number of other ways of preserving the trace are available, depending on the time span of the event. A long-persistence phosphor may hold the display for many seconds while it is sketched or photographed, or the display can be held on the face of a storage scope for many minutes.

timing

When a single event transpires in nanoseconds, the time needed for signals to arrive at their destination must be considered. A working estimate of signal speed in a wire is 20 centimeters per nanosecond. The event will be displayed only if the horizontal movement of the beam occurs coincident with the vertical response to the signal amplitude. If the display is to be photographed, the shutter must be opened before the event and closed afterward. Provision must also be made to insure that only one horizontal traverse of the beam occurs while the shutter is open.

All this implies a trace-recording *system*, rather than an assemblage of generators, amplifiers, cathode-ray tube and camera.

system considerations

vertical

Fig. 1-2 is an elementary diagram of such a system. Block *V*, that receives the input signal, includes a pickup device to translate the signal to an electrical form usable by the system. The functions of *V* may include attenuation, trigger takeoff, input switching and operations that include vertical windowing, differential measurements and signal-sampling inputs as well as amplification and signal delay.

The objective is to apply to the deflection plates a signal which presents a display that is a true analog of the original signal. Because the bandwidth is usually wide, random noise is brought in with the signal, and is difficult to subordinate. Regular noise from power supplies and various waveform generators affects the signal and may broaden the trace with vertical jitter. The driving amplifiers must supply enough power to drive the vertical deflection plates fast enough for the beam to respond to the signal.

horizontal

The *H* block accepts a trigger either from *V* or externally and may regenerate it internally for better sweep control. Here switching signals may be generated to switch multiple inputs, gates are generated to control sweep repetition rate and duration, and for unblanking the beam. The sweep ramps are generated as well as sweep-switching signals, and finally the sweep ramps are amplified and applied to the horizontal deflection system.

trigger

The reference for beginning the sweep must be held at a precise voltage level because any variation introduces sweep jitter and broadens vertical components of the display. The integrity of the trigger system must be protected against spurious trigger signals.

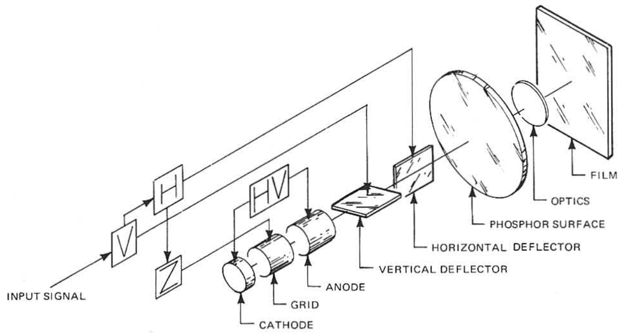

Fig. 1-2.

Z axis

The Z-axis (unblanking) amplifier must respond quickly enough to provide full intensity of the trace before the beam arrives at an important feature of the display. Some applications require modulation of the beam (similar to TV video); the modulation possible depends on the characteristics of the amplifier and the CRT cathode-grid circuit load.

There are five major elements in a trace-recording system:

1. Electronics
   a. Source
   b. Signal pickup
   c. Amplifier
   d. CRT deflection

2. CRT Beam
   a. Current density
   b. Final voltage

3. Phosphor
   a. Efficiency
   b. Spectral characteristics

4. Optics
   a. Magnification
   b. Lens speed
   c. Resolution and contrast

5. Film and Processing
   a. Sensitivity (speed)
   b. Resolution
   c. Contrast

recording system determined by time-response needed

The characteristics of the signal and its source determine the recording system to be used. If the record covers a long period of time, and the incidents occur over milliseconds, a chart recorder may serve better than an oscilloscope. If the incidents occur in microseconds, a scope is needed. If adequate power is available from the source in electrical form, and the rate of rise of the incident is not too fast, the approaches are simple and well known. If a transducer is needed to convert energy to electrical form, the transducer becomes a potential limiting link in total performance. If the source impedance is high, the load of the probe or transducer will have some effect on the behavior of the source; and the extent to which the probe limits the scope risetime depends on probe characteristics. Each element of the signal-processing section determines how close the record or photograph will be to a true analog of the signal.

noise

Problems with electronic noise always exist in a wide-response system, and become more difficult when the signal power is small compared to the noise. If the signal is repetitive, there are means of overcoming noise that is part of the signal. Noise generated within the circuitry is a design problem, but noise is often contributed by faulty arrangements outside the scope, such as stray radiation, noisy cables, and inadequate ground considerations.

beam deflection

The CRT deflection system determines the risetime of the system depending on the physical arrangements of the CRT gun and the power capability of the driving amplifiers. These factors combine to influence distortion of the display. The deflection sensitivity is influenced by the high voltage providing power for the beam.

CRT beam

The CRT beam contributes in great measure to the energy economy of the system, primarily in beam-current density at the faceplate. A fast deflection response demands enough beam power to excite the phosphor at high spot velocity. The higher voltage needed to provide more beam power decreases the deflection sensitivity, calling for more power from the driving amplifiers. An increase in beam power without maintaining spot size may make the trace visible, but too broad to resolve needed information in a low-contrast photograph.

phosphor

The phosphor converts beam energy to radiant energy (including light) and so is one of the five major links in the energy chain. The spectral characteristics of phosphors are most noticeable, but the phosphor efficiency, as well as efficiency influenced by design and process of the phosphor-faceplate relationship, are most significant for photography.

camera

The optical arrangement is the camera design, which determines some of the lens characteristics, and the kind of film suitable. The important criterion for the camera is mechanical and light-tight integrity. Other features are important for particular applications.

lens

The camera is designed to a particular focal length lens, which is one of the major energy links. The lens speed, the coatings and the dominant corrections determine the efficiency of this part of the system. Photographic noise, contrast and resolution are of interest, but in most scope cameras are subordinate to speed.

film and processing

The final element determining the maximum recordable bits per unit time is film and processing. As with the case of the lens, photographic speed is most often the essential criterion, sacrificing contrast and resolution.

energy and power

Most of the measurements made on an electronic system are read out in volts, because it is convenient, and power can be inferred if current or resistance is known. The significant measures that must be known are *energy*, and flow of energy – *power.* Many people, even technicians, confuse the terms. Power is not a quantity, but a *rate*, such as gallons per minute or miles per hour. The term *watts* properly expresses the rate – joules per second. The *joule* (watt-second) is the unit of energy in the MKS system of practical dimensions. The Power Company bills its customers for *kilowatt hours.* One kW-hr equals 60 x 60 x 1000 joules. A 100-W light bulb uses energy at the rate of 100 joules per second. A flashbulb is not rated in watts, but in lumen-seconds, a measure of energy, because the energy is used all at once rather than as a flow.

Light and radiation are measured in terms of power and power per unit area, as well as energy and energy per unit area. There may be a temptation to try and correlate familiar terms like volts and amperes with light values, but the only reliable correlations are those of power and energy.

Noise in electrical systems is most often expressed in terms of power. Signal-to-noise ratio is the ratio of signal power to noise power.

risetime

Risetime is the period required for the circuit to respond to an impulse that rises in zero time. It is usually defined as the time interval between 10% and 90% of the final value of the step.

bandwidth

The direct relationship between bandwidth and risetime is:

$$f_c = \frac{K}{t_r}$$

where f_c is frequency in hertz where the signal is 3 dB down at the high frequency end; t_r is risetime in seconds; and K is 0.35 for less than 1% overshoot (Fig. 1-3).

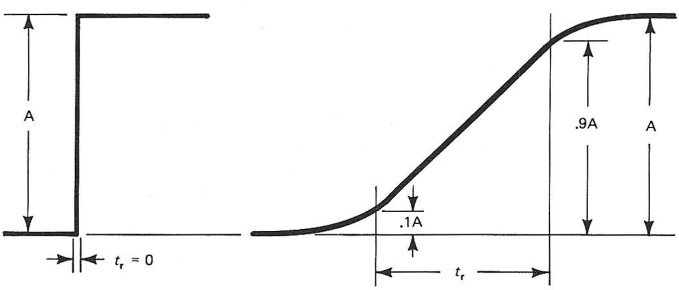

Fig. 1-3.

2

RADIATION AND LIGHT

2.1. RADIATION FLOW AND PROPAGATION*

The velocity of electromagnetic radiation in space, $\approx 3 \times 10^{10}$ centimeters per second, is a fundamental physical constant.

radiation

Fig. 2-1 shows the extent of the electromagnetic spectrum; *light* is that small part that is visible to humans. All radiation has, at various intensities, a noticeable effect on organic matter such as life, as well as on many inorganic substances.

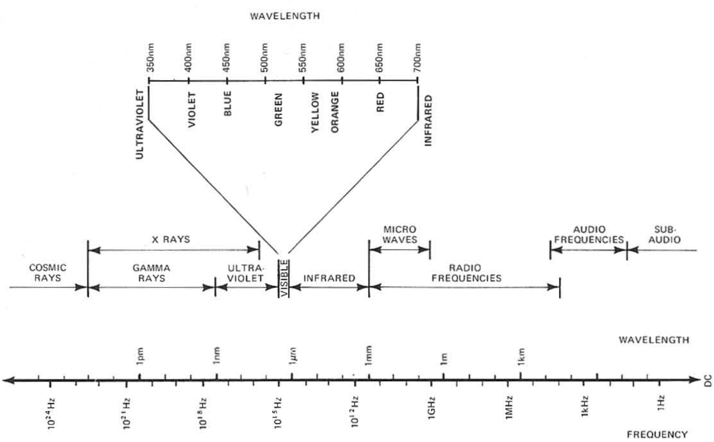

Fig. 2-1. Visible light occupies a very small part of the energy spectrum.

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*Ref: 8. Ditchburn
34. Southall, Ch I
26. Monk, Ch 9-14
31. *Scientific American*, Ch I
16. IES, Ch I

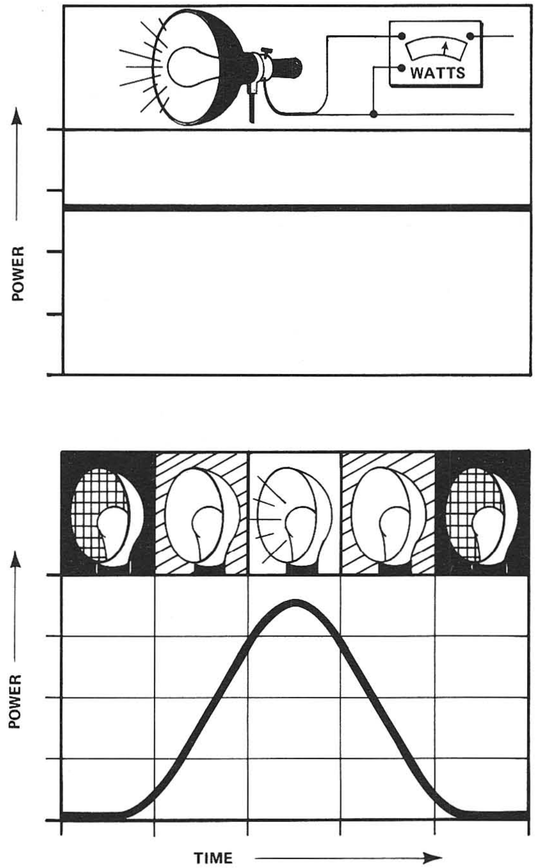

Fig. 2-2. Energy is represented by the area under the curve.

energy and power

Radiation, which includes light, is a form of *energy*. *Power* is the *flow of energy*. Luminous flux (light flow) is measured in lumens. An ordinary electric lamp radiates a *flow* of light, measured in lumens; a flashbulb provides a *quantity* of light, measured in lumen seconds (Fig. 2-2).

light

The response of the average human eye follows the curve shown in Fig. 2-3. This curve defines the word *light* in physical terms. Notice that there is an equivalent power ratio, lumens per watt, for every discrete wavelength (frequency) in the visible spectrum.

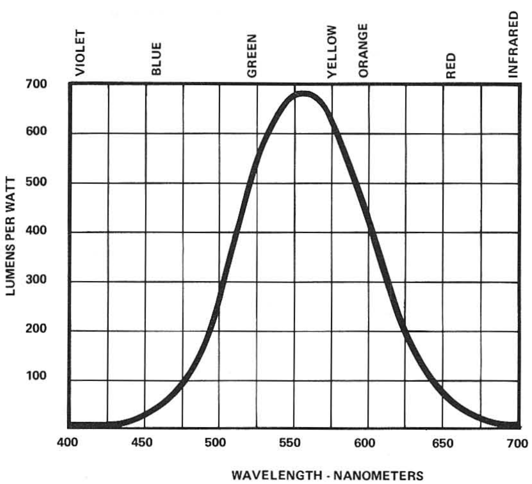

Fig. 2-3. Light is defined by the actual response of human eyes to electromagnetic radiation.

propagation

Fig. 2-4 is an attempt to illustrate the concept of propagation of light. Energy radiates equally in all directions from a uniform source; the wavefronts expand like the layers of an onion. At an infinite distance from the source, the wavefronts lie in planes, normal to the direction of propagation. The intensity of radiation can be expressed schematically as radials which extend from the axis of propagation and as sinewaves, but radiating at all angles – unpolarized. (Light that oscillates in one plane is said to be polarized.) There is attenuation of light only by interposition of material. Each photon retains its assigned energy quota, $E_e = h\nu$, throughout its lifetime. For all our discussions, light travels in straight lines, even in fiber-optics devices.

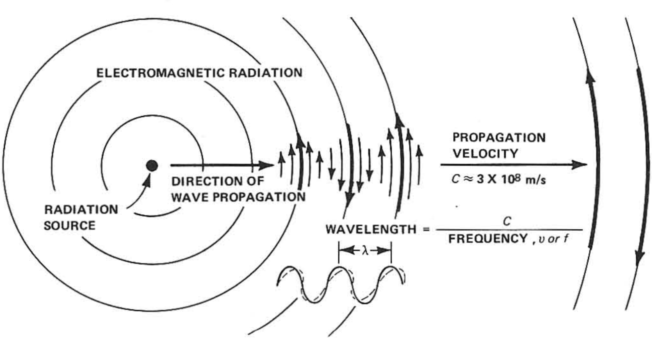

Fig. 2-4. The propagation of light from a point of radiation.

2.2. DIFFRACTION*

An effect that pertains to all forms of radiation is *diffraction*, by which light appears to bend around sharp edges. An acceptable concept is illustrated in Fig. 2-5 where new point sources *appear* to originate at the edge of the light barrier (Huygen's Principle). Some of the light is redirected into the shadow area and some into the clear area. If monochromatic light is used, the diffracted light will be of different phase than the original light, and at a reference plane close to the barrier a pattern of light and dark bars will occur.

Now if the obstruction has a round aperture, concentric circles will appear instead of bars (Fig. 2-6). (The dimensions of these patterns are not much greater than the wavelength of light, and cannot be resolved by the eye alone). The ultimate resolving power of a lens is limited by diffraction. Diffraction affects all photographic processes in which light is restricted by a barrier with a sharp edge.

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*Ref: 26. Monk, Ch XII
31. *Scientific American*, Ch 1

2.3. PHOTOMETRIC CONCEPTS*

We will need to use the concept of light (energy limited by the eye-response curve of Fig. 2-1) as well as that of radiation because photographic terms and standards are based on this curve. We will correlate light quantities with corresponding quantities of electromagnetic energy.

terms

The terms for quantities used in *photometry* are confusing because we need to discuss light as energy, as power, as energy density, as power density, as incident, as reflected and as transmitted, and also remember whether we are dealing in British or metric units.

units

Photometry is discussed mostly in terms of British units because most commonly-available equipment is calibrated in those units, and because many are fluent only in British-system quantities. Note that the USAS Standard and all international standards are defined in terms of the metric system.

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*Ref: 42. Walsh
26. Monk, Ch V
25. Meyer-Arendt
16. IES, Ch IV
21. Kodak (j)

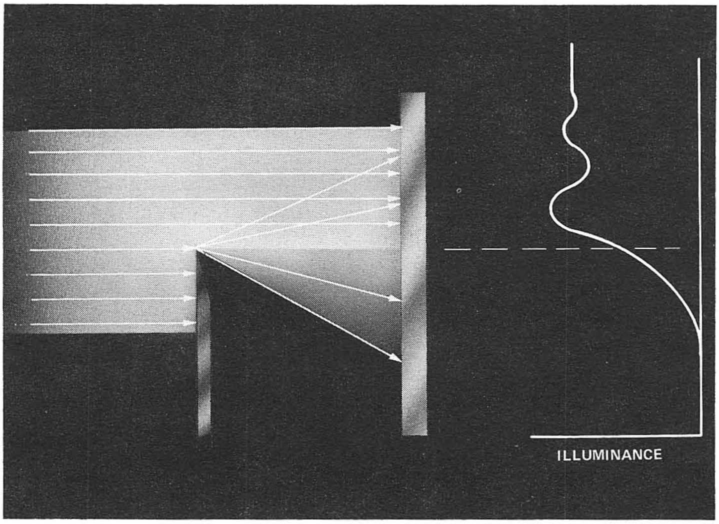


Fig. 2-5. Edge diffraction.

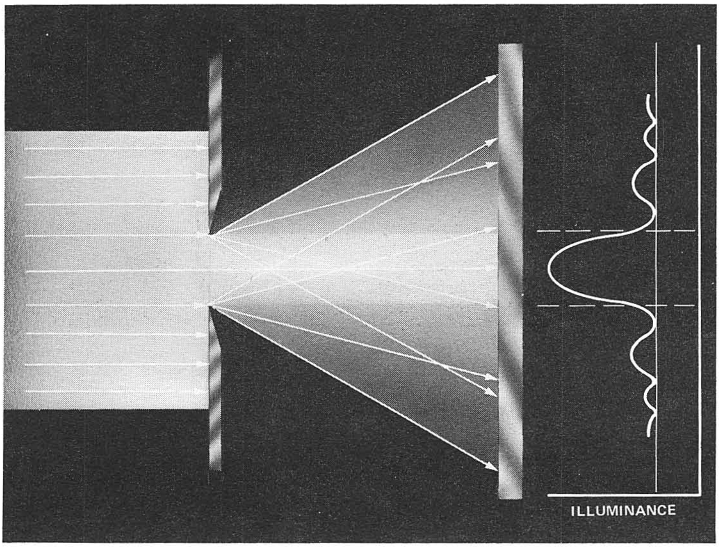


Fig. 2-6. Diffraction at an orifice.

luminous flux

lumen

The standard unit of luminous flux (power), the *lumen*, can be equated directly to watts. At a wavelength of 555 nanometers, one watt = 680 lumens. Other photometric quantities derive from lumens.

lumens per square foot

footcandles

If light from a point source is flowing through space, and we construct a window to limit the quantity of light, we can talk about the number of lumens (power) flowing through the window, as in Fig. 2-7. Regardless of how far the light travels, this particular beam will always contain the original flow of lumens; the power continues until absorbed by some intervening object. However, the luminous *density*, lumens per square foot (or footcandles), will decrease by the square of the distance from the source:

$$E = \frac{\Phi}{A} = \frac{I}{d^2}$$

where Φ = luminous flux
A = area of the window
I = luminous intensity
d = distance from source

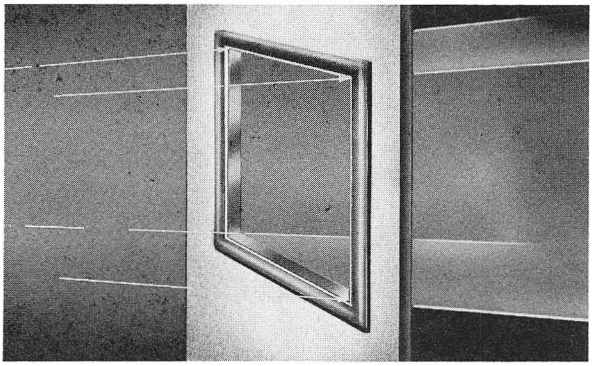


Fig. 2-7. Luminous flux.

In Fig. 2-8, I set up a slide projector 5 ft from the wall and measured one side of the light patch to be 12 inches. A measurement of incident light (the exposure meter facing the projector) reads 32 lumens per square foot. Then I moved the projector back a distance 10 ft from the wall. The same side of the light patch now measured 24 inches but the incident-light reading was now only 8 lm/ft^2.

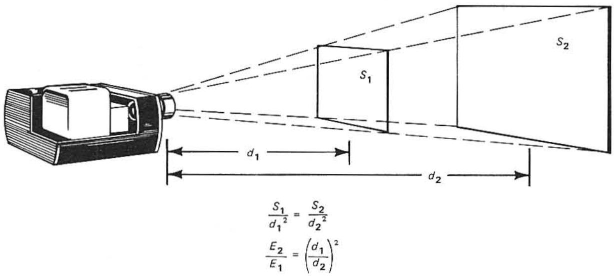


Fig. 2-8. Illuminance, $E = \dfrac{I}{d^2}$.

Luminous flux (for our environment) travels in straight lines. If it radiates from a point, the surface *density*, flux per square foot, will decrease as the square of the distance, but the flux remains the same. In the above example, the flux would be 32 lumens regardless of the distance.

steradian

If I have an ideal point source, a lamp with no dimensions, hanging in space, it will radiate power equally in all directions. The surface area of a sphere is equal to $4\pi r^2$. If we isolate one segment of the sphere by dividing the surface area by 4π, we have a surface area of r^2, which is the area subtended by a *steradian*. On any sphere, if we define an area equal to the square of the sphere radius, we have defined a *unit solid angle* called a *steradian*. This convenience allows us to evaluate, at any distance from the source, the light-flux density at that radius distance. Note Fig. 2-9; the solid angle need not be symmetrical.

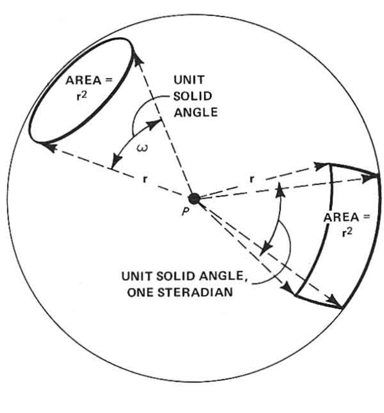


Fig. 2-9. Steradian.

candela

If the luminous flux in the steradian shown in Fig. 2-9 is equal to one lumen, the *luminous intensity* of the source is one *candela.* One candela radiating equally in all directions emits 4π lumens. The term *candela* now replaces the term *candlepower.*

illuminance

When light falls on a surface, the surface is *illuminated* and the measure of the light per unit area is *illuminance.* Illuminance is a measure of luminous flux density received by a surface. If the direction of the light is normal (perpendicular) to the surface, Fig. 2-10, the illuminance (*incident light*):

$$E_e = \frac{\Phi}{A}$$

where A is the surface area. E_e can be expressed as lumens per unit area. There are many terms used to express luminance, depending on the linear units used. We will avoid these in the discussion and refer to Table 2-1 for conversion to other systems.

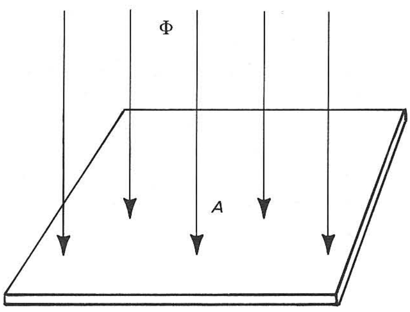


Fig. 2-10. Illuminance, $E_e = \frac{\Phi}{A}$.

cosine θ

Fig. 2-10 shows the incident light *normal* to the surface. If the light falls at an angle to the normal, θ, as in Fig. 2-11, the surface receives only s'/s, or $\cos\theta$ times as much flux per unit area as if the light were normally incident. This cosine factor enters into a number of other calculations.

$$E_e = \frac{\Phi}{A} \cos\theta .$$

POWER: LUMINOUS FLUX, ϕ; INTENSITY, I

INTENSITY OF 1 CANDELA = FLUX OF 4π LUMENS

1 CANDELA = 4π LUMENS

680 LUMENS AT 555nm = 1 WATT

POWER DELIVERED TO A SURFACE (INCIDENT LIGHT): ILLUMINANCE, E

LUMENS PER SQUARE FOOT = FOOTCANDLES

LUMENS PER SQUARE METER = METERCANDLES

FOOTCANDLES = 10.76 METERCANDLES

680 FOOTCANDLES (λ = 555nm) = WATTS PER SQUARE FOOT

POWER REFLECTED OR RADIATED FROM A SURFACE: LUMINANCE, L or B

FOOTLAMBERTS = $\frac{1}{\pi}$ CANDLES PER SQUARE FOOT

FOOTLAMBERTS = 929 LAMBERTS = 929 LUMENS PER SQUARE CENTIMETER

ENERGY = POWER (CONSTANT) X TIME

METERCANDLES X TIME = METERCANDLE SECONDS

WATTS X TIME = WATT-SECONDS = JOULES

1 JOULE = 10^7 ERGS

1.47 METERCANDLE SECONDS = 1 ERG PER SQUARE CENTIMETER (λ = 555nm)

Table 2-1. Photometric relationships.

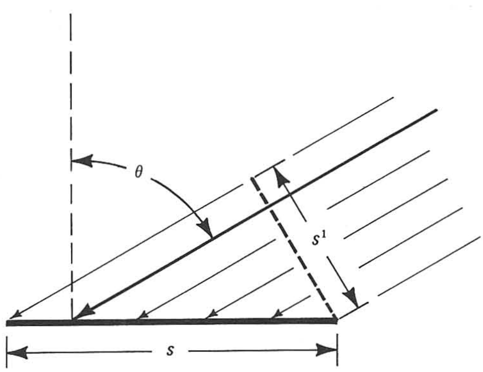
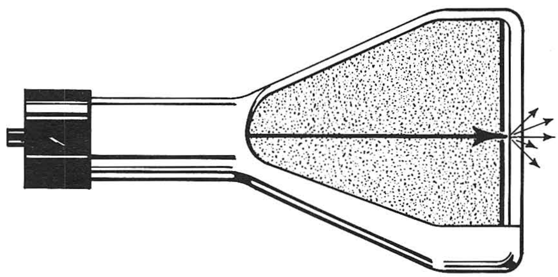
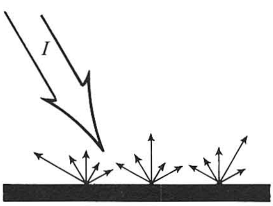


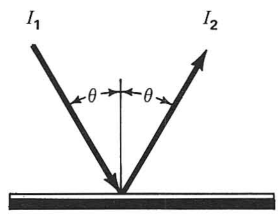
Fig. 2-11. Illuminance, $E_e = \frac{\Phi}{A} \cos\theta$.



(A) Luminance generated at a diffuse surface.



(B) Luminance reflected from a diffuse surface.



(C) Specular reflection $I_2 = \rho I$ where ρ is reflectance.

Fig. 2-12.

luminance

Until now we have been talking about light from a *point source*, a source with a surface area too small to affect measurements; for example, the *apparent* size of a star. Most photographic work is concerned with luminous surfaces of finite areas, and we have to see these surfaces as composed of an infinite number of point-source radiators. This radiation is termed *luminance* and may arise from a source such as an excited CRT phosphor, or it may result from diffuse reflection of other illumination (illuminance) as in Fig. 2-12 A & B.

specular

Note that *specular* reflection (Fig. 2-12C) does not behave in this manner, but reflects all the flux at the same angle with the normal at which it entered.

luminance of phosphor multipoint source

foot-lambert

When a crystal of CRT phosphor is excited by the electron beam, the photons are emitted in all directions as in Fig. 2-13. Part of the flux is reflected by the aluminum, and part is dissipated in the phosphor and the glass. The effective light appears on the inside surface of the glass, in the CRT spot. The spot has a finite area that can be measured, and contains thousands of point-sources, each with a very short lifetime. The resulting *luminance* arises from an *area,* not from a point, and the measurement of this power must be in terms of intensity per unit area. One *foot-lambert* is equivalent to one lumen per square foot of a very large, uniformly diffuse radiating area (Lambert's Law).

brightness luminance

The symbol for luminance is L; the term *brightness* is used in older texts. *Brightness* is now applied to the subjective evaluation, that is, the *apparent* amount of light, and *luminance* is applied to a measurement of light.

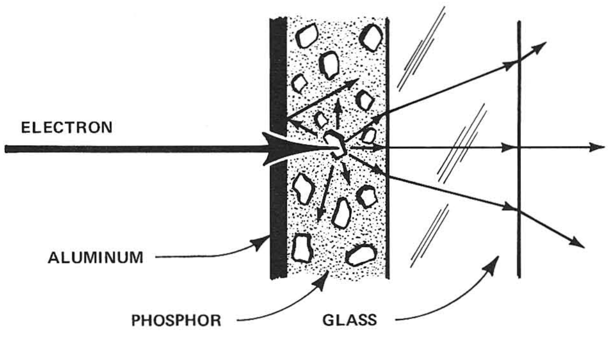


Fig. 2-13. Diffuse radiation.

Lambert's cosine law

If we have a merged raster on a CRT so the face is uniformly luminous, a small area of the surface is a *diffuse* radiator. If we direct a light meter with a narrow acceptance angle toward the CRT surface, the reading will not change as we change its distance from the screen, or as we change the angle it makes with the CRT axis (Fig. 2-14).

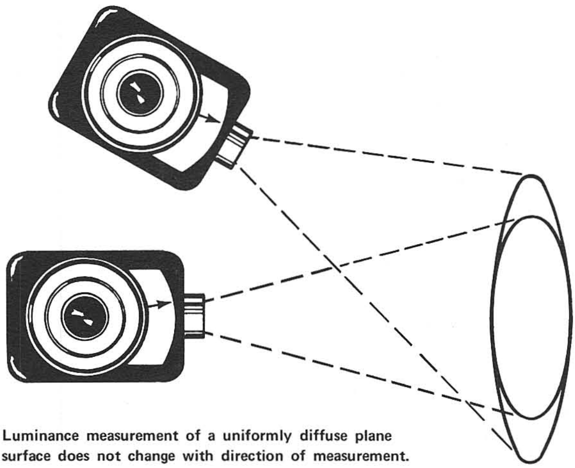
Increasing the distance decreases the flux received from each individual point-source, but also increases the number of point-sources measured.

As the angle of measurement is changed from normal, the meter receives less flux from each point source, but receives flux from more sources.

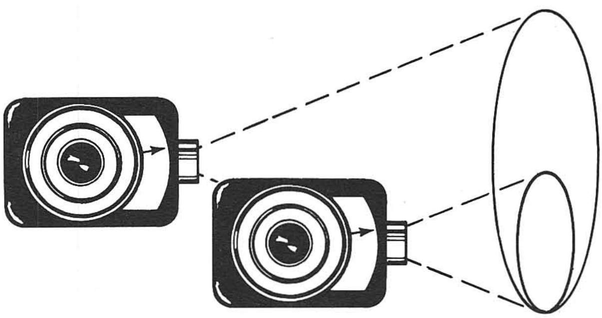
Be sure to differentiate between light received and light emitted, and also between light from a point source and light from an area of a diffused source.

reflectance

When light falls on a diffusely reflecting surface, the surface behaves as a diffuse radiator, and the same principles are in effect. The power reflected will depend on how much light has been lost by passing through the surface, or by being absorbed (heating) in the surface. A factor used to define the losses is *reflectance.* A very efficient reflecting surface, such as magnesium oxide, may reflect 98% of the light; a plain piece of paper may reflect only 50%. Photographers have trouble with snow scenes because of the high reflectance of snow compared to other elements of the composition. For this reason, most exposure meters provide for two kinds of measurement: Incident light density in footcandles (lumens per square foot) or reflected light, based on a reflectance of about 0.18.



Luminance measurement of a uniformly diffuse plane surface does not change with direction of measurement.



Luminance measurement of a uniformly diffuse plane surface does not change with distance.

Fig. 2-14.

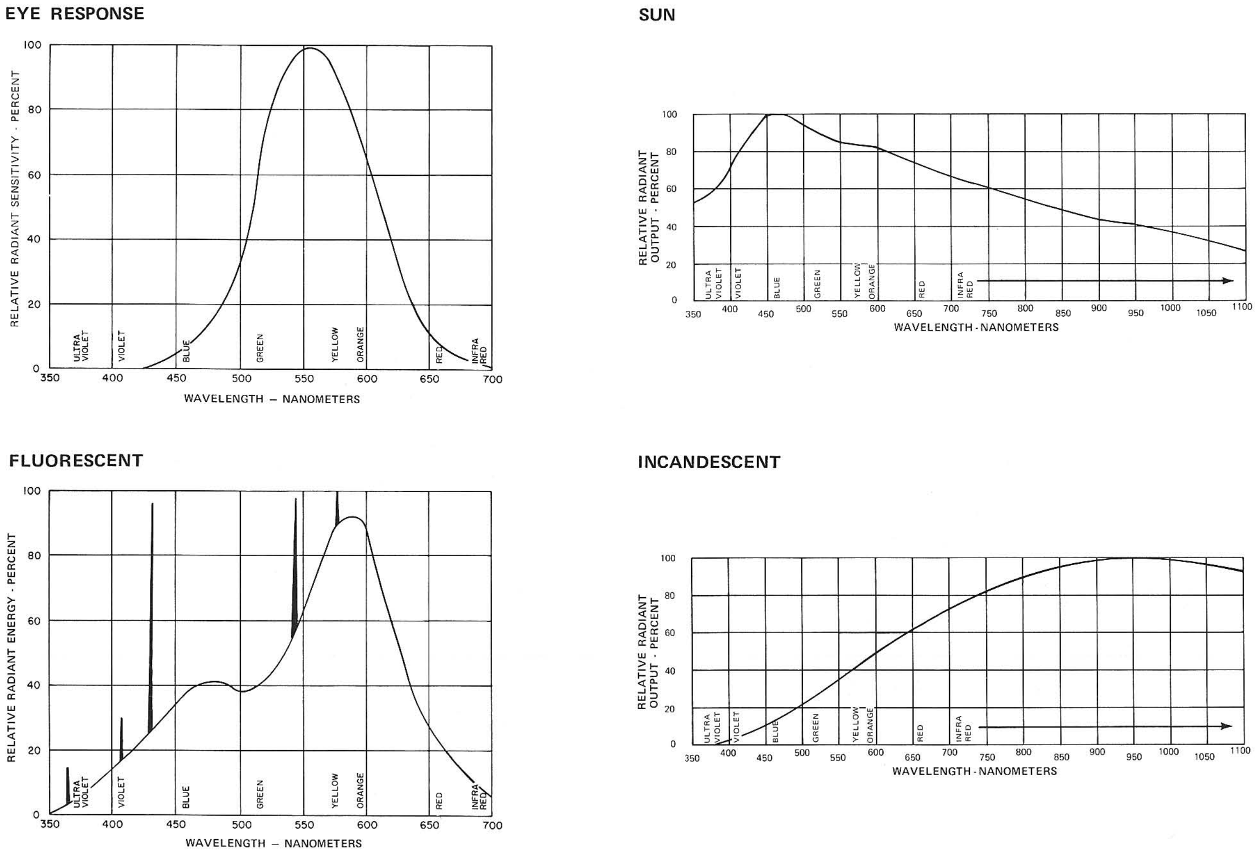


Fig. 2-15. Comparative spectral patterns of light sources.

2.4. LIGHT SOURCES*

incandescence

Incandescence is the effect of general electron displacement in gases and solids at high temperatures. Radiation from incandescence covers a broad, continuous spectrum.

luminescence

Luminescence results from selective electron displacement in gases and solids (including organic solids) due to electromagnetic, chemical, biochemical, radiation, kinetic and thermal effects. Luminescent radiation appears as line or band spectra.

sunlight

The most obvious light source is the sun, because we have become accustomed to viewing our environment by sunlight, either directly or diffused. Our color values and sense of shadow have been established by the spectrum we receive from the sun. However, most photographic work requires a source of light that can be available and controlled at any time and place. The term "artificial light" is a contradiction sometimes used to denote a light source other than the sun. The characteristics of all light sources depend on the source and the operating parameters. Even sunlight varies in spectrum and intensity depending on time, season, location and local conditions. General-use film emulsions are designed with wide latitudes to accommodate these variations. They become limiting when color film or highly specialized emulsions are used.

"artificial" light

Incandescent lamps (photoflood) are still used and continue to be developed to provide convenient sources with spectra that can be accommodated by special film types and by filters. Light from luminescent gas has the advantage of efficiency: Relatively low heat dissipation; but their spectra have great narrow-band energy peaks that must be accommodated. The electronic flash provides a large burst of energy (lumen-seconds) and can be synchronized to observe rapidly moving objects.

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*Ref: 23. Leverentz
36. Sproull, Ch 10, 12
16. IES, Ch 1, 8

lasers

Another very interesting source of light is the laser, which generates a truly monochromatic light of high intensity, and provides a tool for many investigations and developments not formerly possible. At this time, photographic use of lasers is limited to very specialized applications.

The light source of most interest to us, luminescent solids (phosphors), will be covered in Chapter 4.

COMPARATIVE LUMINANCE VALUES	Approximate footlamberts
Snow in full sun	5000
Clear sky	1000
Recommended office illumination	100
Black and white TV screen	100
Classroom slide projector	10

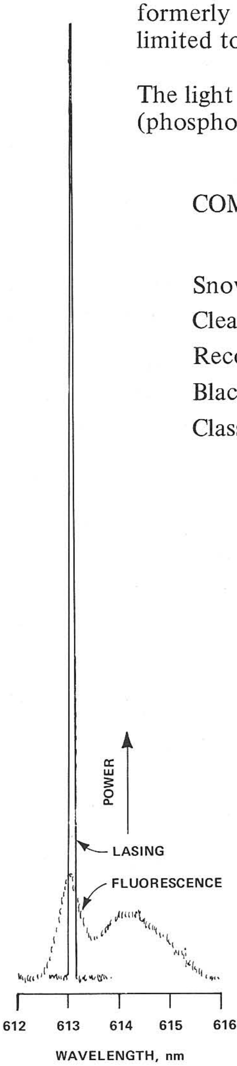

Fig. 2-16. Power distribution: Fluorescence vs lasing.

2.5. COLOR*

Color is often considered a property of materials or objects; a careful description of an object will describe its color in subjective terms. Color, however, is not actually a physical property, but the result of the action of the eye discriminating energy at particular wavelengths. The eye is the original spectrum analyzer.

filters

Materials observed have molecular or crystalline structure that filters light selectively. We earlier mentioned that light includes radiation of all wavelengths in the visible spectrum.

Light is always transmitted through a medium, dissipated in a medium, and reflected from a medium, in some measure, however small. Light coming through a translucent medium is selectively filtered; that is, radiation at some wavelengths is absorbed or scattered by the material. Those not absorbed pass through (some will be reflected) (Fig. 2-17). A color filter, such as used in photography or on the face of an oscilloscope, will have the hue of its transmission characteristics. A filter that appears blue passes the high (short-wavelength) end of the spectrum and attenuates the lows.

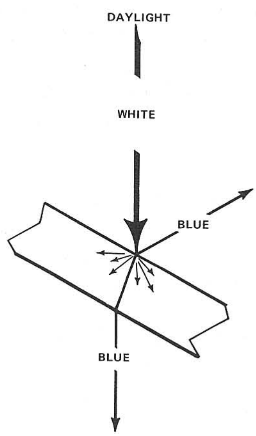

Fig. 2-17. Translucent material absorbs or scatters light of some wavelengths.

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*Ref: 11. Evans
12. Kodak (b)
19. Judd
31. *Scientific American*, Ch 1
32. *Scientific American*, Ch 1
16. IES, Ch 5
27. Neblette, Ch 34

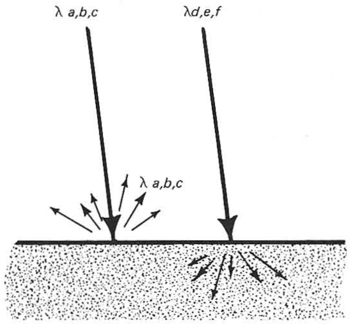

Fig. 2-18. Different materials absorb light of certain wavelengths; the wavelengths reflected determine color.

reflection

The color characteristics of opaque objects obtain from selective *reflection* of light (Fig. 2-18) and involve different processes than those of light transmission. A mirror (L. speculum) reflects all colors faithfully by *specular* reflection, wherein the surface is highly polished, so that each ray of light is reflected precisely at the same angle at which it struck the surface. A diffuse surface may reflect a high percentage of incident light (magnesium oxide surface about 99%) but the individual microsurfaces lie in planes that are not parallel with the gross plane. The law of incidence and reflection is the same as for specular light, but the values of the angles of incidence are random. Most diffuse surfaces are selective, reflecting the colors we perceive.

color mixing

Light from a set of primary colors (red, blue and green, for example) can be mixed in combinations which appear as a "pure" color, corresponding to a narrow band of the spectrum. This primary mixing process makes possible all the synthetic colors used in graphics, photography, television and other common processes.

hue
brightness
saturation

Colorimetry, the measurement of color, is referenced to three dimensions: *Hue*, referring to the spectral position; *brightness*, referring to the light power radiated, and *saturation*, referring to the ratio of the narrow-band power to the broad-band power. The perception of color is subjective, like the recognition of brightness, so arbitrary systems of color measurement had to be established. Colorimetry is a complex subject; its study is best approached from the particular needs of the reader.

color temperature

Color temperature refers to the temperature of an incandescent black body, a theoretically perfect radiator. The reference, in degrees Kelvin, is applied to light sources operating under specified conditions. These sources with selected filters provide color values adequate for illustration processing and color television display tests.

3

RECORDING MATERIAL & PROCESSES

3.1. GENERAL PRINCIPLES*

A silver-halide emulsion is used as the recording medium for nearly all CRT photographic operations requiring fast response. Other media, providing advantages for peculiar situations, will be mentioned later. A comparison of merits of several media is shown in Table 3-1.

	SENSITIVITY cm^2/erg	RESOLUTION lines/mm	INFORMATION CAPACITY $bits/cm^2$
SILVER HALIDE			
FAST	1000	50	10^5
SLOW	60	100	$4 \cdot 10^5$
SPECIAL	10	>2000	10^8
XEROGRAPHY	1	100	$5 \cdot 10^3$
DIAZO	10^{-7}	>1500	10^8

Table 3-1. Comparative film characteristics. Order-of-magnitude figures at ≈450 nanometers.

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*Ref: 24. Mees
22. Kosar
27. Neblette, Ch 12
12. Gurney and Mott, Ch 7

emulsion

The emulsion consists of a gelatine compound into which silver halide salts have been mixed according to precise formula and process. The constitution of the gel, which is similar physically and chemically to the edible form, must satisfy several criteria. It must remain perfectly stable at reasonable conditions of temperature before use; and after processing, remain chemically and physically stable for long periods under broad conditions of temperature, humidity and handling. The gel holds the silver halide crystals in suspension in an even distribution, and provides a means of controlling the size of the crystals. Also, the coating of gel on the crystals serves to inhibit reduction (development) of unexposed crystals. The gel also influences the photographic speed of the film.

silver halides

The silver halides – silver chloride (AgC1), silver bromide (AgBr), and silver iodide (AgI) – are the light-sensitive elements in the emulsion. Photons (light) striking the chemically quiescent emulsion release electrons from the halide ions; these electrons meet with silver ions to form atoms of free silver in the crystal. (This is only a rough approximation of the process).

silver atoms

silver molecules

The yield of free silver atoms is not more than one per 4 to 100 photons actually absorbed by the crystal, and the lifetime of a single silver atom is only on the order of seconds, before it recombines or loses an electron. If another atom of silver is formed adjacent to the first one, a stable molecule is established. Now additional silver ions in the same crystal, converted by free electrons, will readily assemble with the free silver molecule. These atomic incidents presumably occur between atoms on the crystal surface, ionized by the gel and the salt molecules (and impurities) that make up the crystal structure. The film is still in a dry state, and may remain so for months, carrying the *latent image* in the centers of free silver molecules.

The above discussion is provided as a workable basis for understanding some of the characteristics of emulsions and processes.

Many serious studies have been made in the last fifty years on the theory of the latent image; some of the most significant work is quoted in the references. At this time, no one theory is universally acceptable and research continues. None of these theories can properly be reviewed here.

development

The water in the developer first softens the gelatine, causing it to swell, permitting access of the reducing agent to the silver ions in the crystal. Where a free silver center has been established in the crystal by exposure, the silver ions reduced by the developer will begin to congregate rapidly, until in time the whole crystal will become a chunk of silver. The unexposed crystals will be reduced also, but at a much slower rate, because unless the silver atoms can collect other silver atoms, they recombine with the halides. The development process can multiply the effect of a few photons by the average silver-ion population of the crystals. This is why the silver-halide recording process is more sensitive than anything other than electronic camera tubes. It is important to note that the Polaroid* process begins with the same silver-halide emulsion and development process.

spectral response

The response of an emulsion without sensitizing dyes is limited to wavelengths shorter than 500 nanometers, and depends on the proportions of AgBr, AgCl and AgI. These emulsions would respond well to a P16 and other phosphors in the blue region, but for general photography they wouldn't be adequate. The emulsion response can be extended well into the infra-red region ($\approx$1100 nm) or tailored to respond to specific spectral regions in addition to their normal response by the application of selective dyes. A selected cyanine dye, included in the emulsion, coats each crystal and allows it to respond to a wavelength complementary to the color of the dye. Orange-colored CRT phosphors, such as P21 and P27, do not record well on orthochromatic film.

grain size

For most photographic work, grain size is important because it is a major source of noise, and it limits resolution. Grain size depends on the size of the silver halide crystals in the emulsion as well as on processing conditions, although grain size is not the same thing as crystal size. Crystal size varies from a maximum of 2 or 3 microns down to 1 or 2 nanometers. The most sensitive materials have larger grain size as well as wider size distribution. Fine-grain films, used for big enlargements, are much less sensitive. For oscillograph records, we are seldom concerned with grain size, and film is chosen for other features, usually sensitivity (film speed). Grain size is of first importance for work in microfilm and spectrography, where high resolution is essential.

sensitivity

The sensitivity of a film depends on the light being *absorbed* by crystals; physical considerations determine optimum crystal concentration in the emulsion. Fig. 3-1 illustrates energy absorption by the crystals, necessary to create a latent image. If crystal population density is thin, much of the light will pass through without direct effect.

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*Registered Trademark Polaroid Corporation

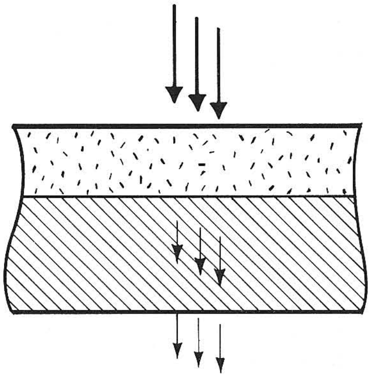

Fig. 3-1. Energy absorption depends on population density of exposed crystals.

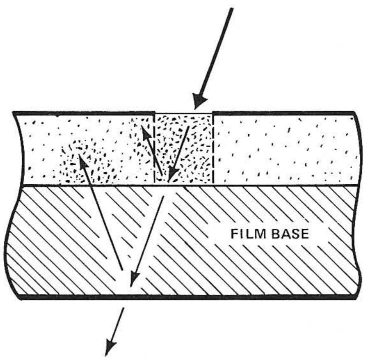

Fig. 3-2. Halation results from light reflected from film interfaces, primarily the back side of the film.

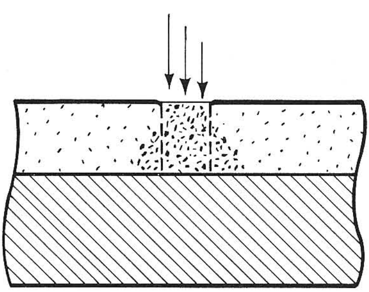

Fig. 3-3. Loss of resolution due to scattering.

halation

Fig. 3-2 illustrates halation effect. Part of the light not absorbed by the emulsion is reflected from the surfaces of the film base. The remainder is dissipated in the environment at the back of the film. Most films are now provided with an antihalation dye on the back surface, which absorbs the light that has passed through the film before it can be reflected. Halation contributes noise and poor resolution.

electron scatter

Exposure in high-illuminance areas of the image may contribute to poor resolution because of scattering within the emulsion, as shown in Fig. 3-3. The electrons resulting from photon excitation are emitted in random directions, so the boundaries of the latent image are poorly defined. This reaction is more evident with thick emulsions and overdevelopment.

3.2. DENSITOMETRY*

density

Photographic density is a measure of the energy per unit area received by the sensitized material.

If light of luminous intensity I_1 is measured on the source side of the sample (Fig. 3-4) and the measurement on the other side is I_2,

then *transmission*, $T = \dfrac{I_2}{I_1}$

and *opacity*, $O = \dfrac{1}{T} = \dfrac{I_1}{I_2}$

and *density*, $D = \log O = \log \dfrac{I_1}{I_2}$

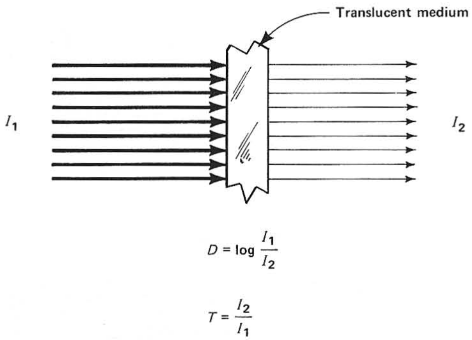

Fig. 3-4. Defining *transmission* and *density*.

*Ref: 1. ANSI (c), (e)

transmission density

Unless otherwise specified, *density* implies *transmission* density; the measurement must be made on a translucent material. A different arrangement is made for *reflection* density, performed on opaque materials.

Notice that transmission is always less than one; the term is also used as a factor applied as a measure of lens efficiency. Density is so calculated that a positive logarithm is always expressed.

densitometer

A photometer is a device for measuring intensity of light. A number of types are used for particular purposes; the photographic exposure meter is a type of photometer. The density of an area of film is measured by a special kind of photometer: a *densitometer.* Some densitometers measure directly the ratio of transmitted light to incident light.

A simpler method is to compare transmittance through the sample with that through a calibrated density scale: a neutral density filter, calibrated in steps, or continuously (*wedge*). Fig. 3-5 shows the schematic arrangement of the comparison type; the neutral density filter may be calibrated to any system, or be a continuous-scale wedge. Steps from $D \doteqdot 0.05$ to 3.05 are commercially available in increments of 0.15, equivalent to a power ratio of $\sqrt{2}$.

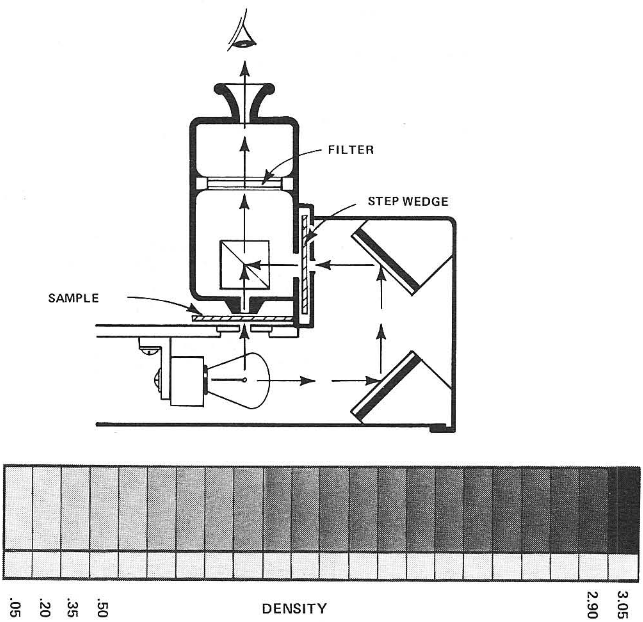

Fig. 3-5. Simple densitometer.

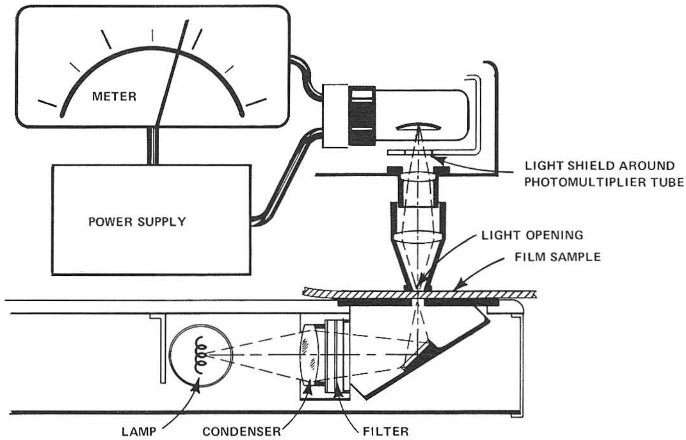

Fig. 3-6. Direct-reading densitometer.

A direct-reading type shown schematically in Fig. 3-6 uses a light source calibrated electrically before each use, allowing the light transmitted through the sample to be measured by a photomultiplier, also calibrated. This type is easy to use and adequately accurate for commercial work.

For more precise measurements of resolution, grain, noise and sensitivity of very small areas, a microdensitometer is used.

3.3. SENSITOMETRY*

characteristic curve

Density versus energy relationships are usually expressed by some form of the *characteristic curve*, or H and D curve, shown in Fig. 3-7. The ordinate scale begins with a density of 0.0, representing a light-power transfer ratio of one, or perfect transmission. The scale is extended vertically as far as necessary; in most cases a density of 3.0, representing a power loss ratio of 1000, is adequate. The exposure scale is usually expressed as the logarithm of light power · time: Log metercandle-seconds, or sometimes log ergs per square centimeter.

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*Ref: 24. Mees, Ch 4, 19, 20
12. Gurney and Mott, Ch VII
13. Hamilton
27. Neblette, Ch 20, 24
21. Kodak (a)(c)(g)(h)(i)
1. ANSI (f)

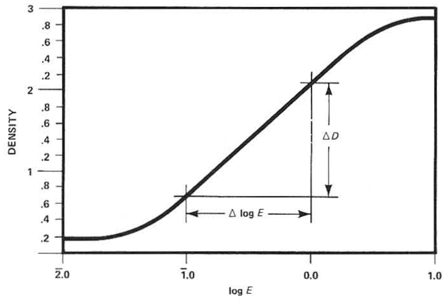


Fig. 3-7. Film characteristic curve (H and D).

processing effects

The *D*-log *E* curve describes the performance of the film under specified conditions of processing: the developer formula and dilution, the mechanical process (tank, tray, agitation), the temperature and the development time. Usually a family of curves is presented, based on identical conditions except for time of development (Fig. 3-8).

gamma

The slope of the curve $\frac{\Delta D}{\Delta \log E}$, over a linear portion, indicates the contrast to be expected. This slope is termed the *gamma*, which is an index of contrast for exposures well above the toe of the curve. However, some exposures are made to use the toe portion for much of the information, such as detail in deep shadows. Under these conditions, an average slope over a wide range of exposure values would be a better indication for determining processing conditions. Eastman Kodak Company uses the term *contrast index*, CI, to describe the *average* slope $\frac{\Delta D}{\Delta \log E}$ of the curve. The distance on the curve, between the two points determining the slope, is equal to log E = 2.0; the lowest point is established where the curve crosses the line D = gross fog (base-density + fog) plus 0.1, as in Fig. 3-9. The slope then defines CI, as used in Fig. 3-8.

contrast index

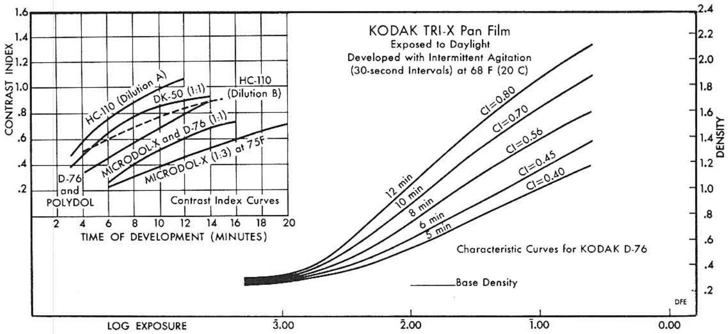
gross fog

The term *gross fog* describes the density of processed film in an unexposed area. The toe of the *D*-log *E* curve falls to this level when extended. Gross fog is the density level where sensitometry measurements begin.

sensitivity

speed rating

Sensitivity is the inverse of the energy-per-unit area required to achieve a specified density on the film under specified conditions of light and processing. Sensitivity is usually expressed as a *speed rating.* For some kinds of work sensitivity relative to an arbitrary standard will be used. Control of the conditions of processing (solution, temperature, and time) must be precise in order to compare film speeds.



NOTE: Reproduced from a copyrighted Kodak publication.

Fig. 3-8. Kodak sensitometric curves.

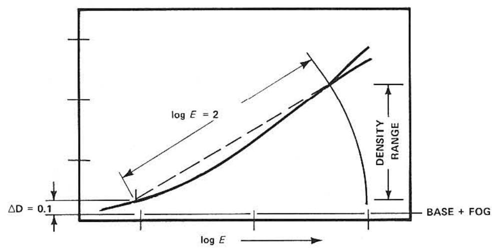


Fig. 3-9. Concept of contrast index.

ASA film speed

The ASA film speed is determined according to ASIS PH 2.5 1960, *Speed of Photographic Negative Materials.* The film samples are exposed to a graduated test strip and processed under specified conditions of development chemistry, temperature and agitation. Time of development is adjusted for several samples, so a family of curves similar to those in Fig. 3-8 can be drawn. After density measurements are made and the curves are plotted, a curve is selected (Fig. 3-10) wherein point M on the curve at $D = 0.1$ plus gross fog is $\Delta \log E = 1.3$ distant from the exposure level where point N on the curve is $D = 0.8$ plus gross fog. Point M then lies at the exposure level E_x used in the expression

$$S_x = \frac{0.8}{E_x}$$

where S_x is the ASA speed of the film and E_x is in meter-candle-seconds. The ASA speed so determined applies to "films intended for monochrome continuous-tone negatives in pictorial still photography." Exposure meters are calibrated in accord with this standard (ASIS PH 2.12 *General Purpose Photographic Exposure Meters*). These speed values are not generally applicable to nonpictorial types of film or to pictorial film used in nonpictorial applications. Film speed values for oscilloscope work are discussed in Chapter 8.

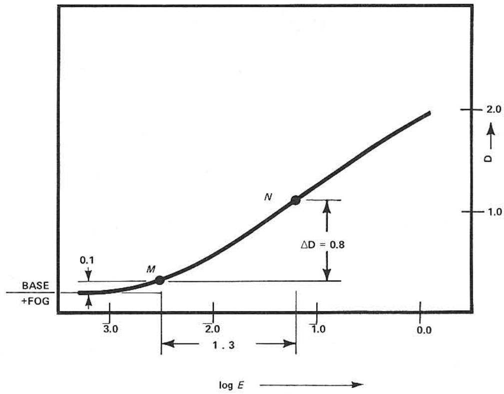


Fig. 3-10. Determining ASA film speed.

reciprocity failure

The characteristic curves for films use log E for the independent variable: E, exposure, is varied and the density changes according to the curve. Notice that E is a quantity of energy received by the film. When the film is illuminated at a constant rate, with I meter-candles, the total energy E will be $E = It$, meter-candle-seconds. This implies that $I \cdot t$ (m-c-s) will always result in the same film density under identical conditions, whether I is small and t large, or conversely. The characteristic curves imply this also. This reciprocity loses validity for time shorter than 0.01 second and longer than 10 seconds; curves are available for most films (Fig. 3-11).

The extremes where reciprocity-failure occurs are in astronomical photographs, where minute illumination is gathered for very long periods, and in oscilloscope photography where only nanoseconds are available to expose the film to the trace.

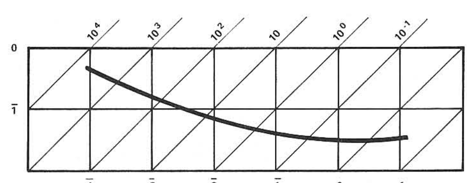


Fig. 3-11. Reciprocity failure.

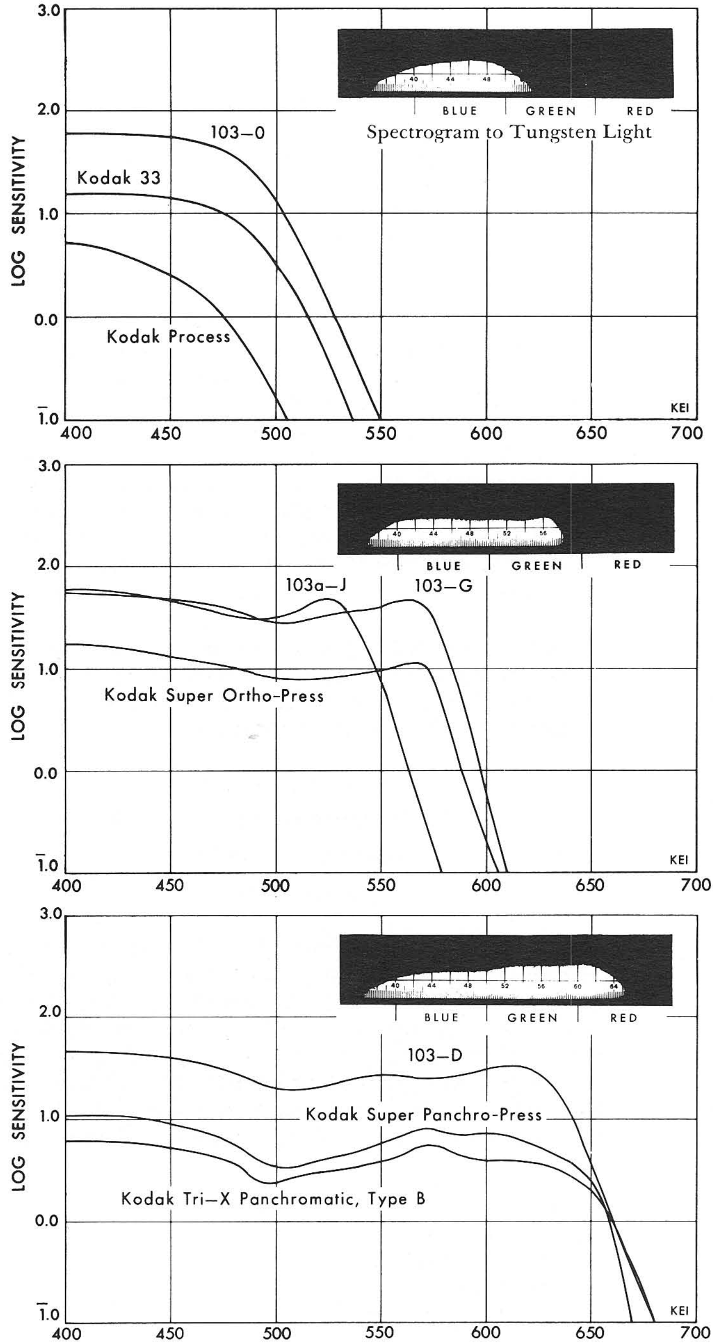


Fig. 3-12. Control of spectral response.

3.4. RESPONSE CHARACTERISTICS AND CRITERIA*

The spectral response curves in Fig. 3-12 indicate that response can not only be extended to the long wavelengths (as far out as 1200 nm), but sensitivity can be maintained over a wide range (panchromatic). Fig. 3-13 shows the response of a diffusion transfer type film on a relative scale.

Fig. 3-14 presents some significant characteristics of a very high-speed film suitable for CRT recording. Chart A compares two indexes of sensitivity; further discussion of sensitivity indexes appear in Chapter 7. Curve B illustrates the effects of development time. Increasing development time usually increases apparent sensitivity and contrast, but also increases fog. The modulation-transfer curves show poorer spatial frequency response for longer development times. The resolving power and granularity of this film are rather poor, but entirely adequate for all CRT recording except for use with special CRT's with extremely small spot size, and where a high-speed film is not required.

resolution

Resolution, or resolving power was defined in Chapter 1 as the minimum distance between two points which could be visibly separated. This is not a complete criterion because several other factors influence detail discrimination:

- Granularity (noise)
- Density difference (contrast)
- Signal-to-noise ratio
- Adjacency effects

granularity

contrast

Crystal grain size was noted earlier in the chapter as a factor contributing to resolution. The developed grain is not necessarily in the same order of size as the original crystal, and the structure of the grain depends on the development process. We are not interested in granularity at this point; an enlargement of a CRT display great enough to show grain is not necessary. Granularity has, however, a significant effect on contrast. If an unexposed film is developed and fixed, the density will be greater than that

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*Ref: 24. Mees, Ch 12, 15, 23
12. Gurney and Mott, Ch 7
27. Neblette, Ch 24
21. Kodak (a)(c)(e)(f)(g)(i)
28. Riesenfeld
29. Perrin
35. SPSE, Ch 3, 7, 10

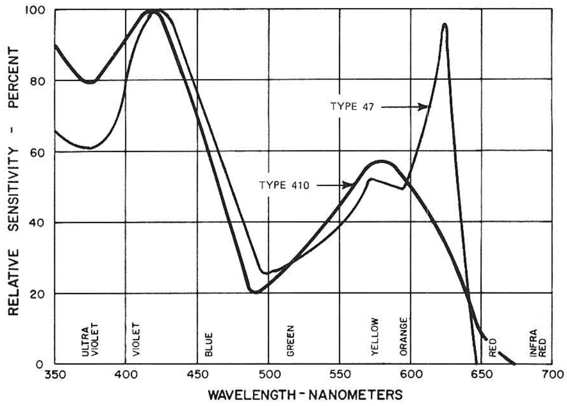


Fig. 3-13. Spectral response of Polaroid films.

of the base alone, because some of the unexposed crystals will be converted to free silver merely by the development process. This

gross fog

level of density, the gross fog, will provide the background for the CRT trace (or the blackest level in a conventional photograph). While the fog appears as a homogenous shade of gray, it is actually a distribution of irregularly-shaped globs. The discontinuity of density between the glob of silver and the clear gel and film

noise

results in photographic *noise* or fog. As the population of these globs increases (in the three-dimension field of the gel), the total density of the projected-area increments take on all values from minimum to maximum; a graph of density versus distance over a thin strip of area appears similar to that of a CRT display of electrical noise, Fig. 3-15. When our photographic step function, zero density to maximum density, is imposed on this background of fog, the edge of the figure blends in with the fog gradually rather than cutting off sharply. Photographic noise results from

signal-to-noise ratio

the random variations in space and density. Photographic signal-to-noise ratio is the ratio of density difference of the image to mean level of random density variations of the background.

Photorecording Sensitivity*	Development Conditions		
	KODAK Developer	Time	Temperature
2500	MX642-1	4 min	90 F (32 C)
2500	MX642-1	2 min	98 F (37 C)
1600	D-19	12 min	75 F (24 C)

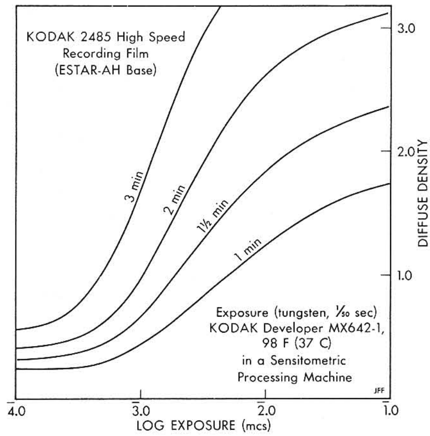
*This figure is based on the reciprocal of the tungsten exposure in meter-candle-seconds required to produce a density of 0.10 above gross fog at an exposure time of 1/10,000 second and with recommended development.

Relative CRT Speeds (P11 phosphor)

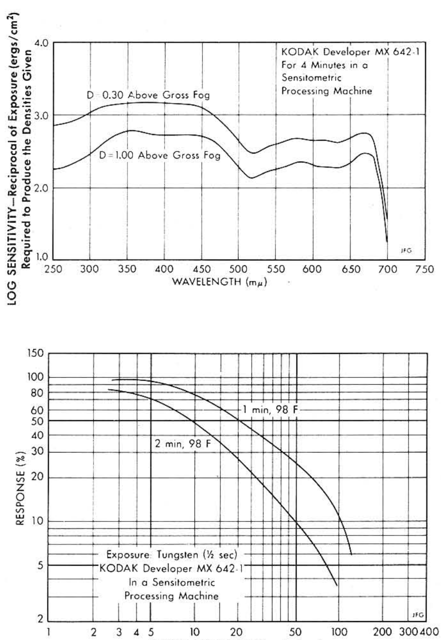
Relative CRT Speed*	Development Conditions		
	KODAK Developer	Time	Temperature
16,000	MX642-1	4 min	90 F (32 C)
10,000	MX642-1	2 min	98 F (37 C)
6,400	D-19	12 min	75 F (24 C)

*Measured at a density of 1.0 above gross fog.

(A) SENSITIVITY CHARTS



(B) DEVELOPMENT CHARACTERISTICS



(C) SPECTRAL SENSITIVITY AND MODULATION TRANSFER CURVES

Fig. 3-14. Kodak 2475.

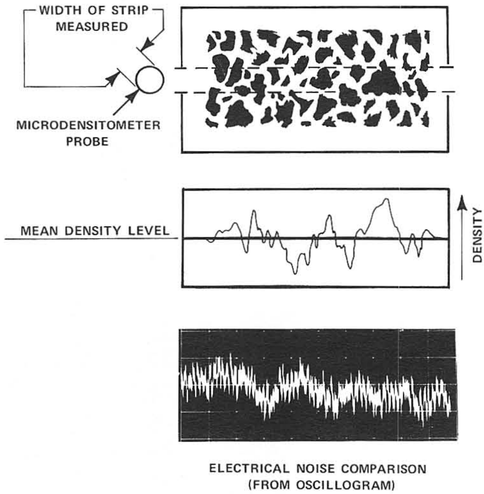


Fig. 3-15. Illustrating volume density of emulsion.

transition degradation

Fig. 3-16 illustrates a concept familiar to electronics technology, the step function. An extreme example would be a photograph of an open doorway in a white house in the sunshine, looking into a completely dark room. The step from dark to light represents an energy ratio as great as 10^6:1 (60 dB), although normal photographic negative densities provide less than 10^3:1 in contrast. Ideally, the transition occurs abruptly; in electronic terms, zero risetime. Actually, the optical system broadens this line by diffraction and light scattering, and the film continues to degrade the step by scattering within the emulsion and by halation effects (Figs. 3-2 and 3-3).

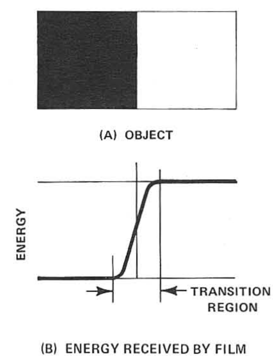


Fig. 3-16.

If we construct a pattern of bars and spaces of continually decreasing width as in Fig. 3-17, remarking that the transition between black and white is gradual rather than discrete, then plot the density of a strip from one end to the other, we will have a plot of sinewaves corresponding to a frequency-modulated signal.

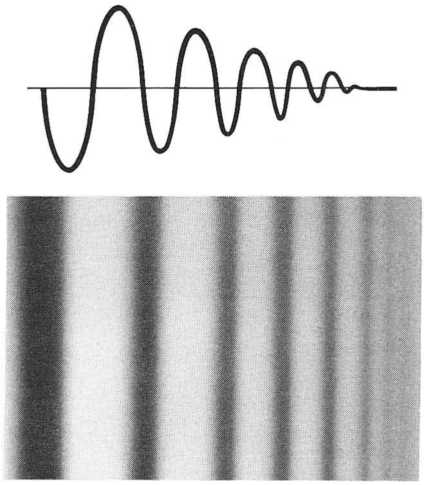


Fig. 3-17. Sinewave pattern of photographic density.

Now, if we photograph the original drawing and again plot the density of a strip from one end to the other, we have a means of assigning a criterion to the film (if we know the lens criterion) by evaluating the difference between the photograph and the original.

Looking at the sinewave plot, Fig. 3-18, we can define modulation as:

$$m = \frac{A_p - A_v}{A_p + A_v}$$

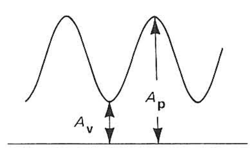


Fig. 3-18.

modulation transfer factor

then, at that spatial frequency, the *modulation transfer factor*, is $MFT = \frac{m_i}{m_o}$, where m_i is modulation of the image, and m_o is modulation of the original.

The amplitudes of the sinewaves decrease as spatial frequency increases because the white spaces are less white and the black spaces are less black as they become more narrow: The frequency response of the system is decreasing. The factors limiting this response are processing fog, light scattering in the emulsion, halation and grain (granularity).

Comparative examples of film MTF are shown in Fig. 3-14 with other film criteria.

adjacency effects

Adjacency effects also influence detail discrimination. The response indicated in Fig. 3-19 shows "overshoot" resulting from developer reactions at the borderline of the step. The exhausted developer from the exposed side flows to the underexposed side and there inhibits normal development. Among other effects, this reaction results in a lower center density in a wide line, and higher center density in a narrow line, and finally, in a very narrow line, a further decrease in density. These edge effects tend to counteract the effect of the optical spread function, resulting in higher acutance than would normally be expected. Because these are chemical effects, they depend on the processing variables – chemistry, temperature, agitation, and time.

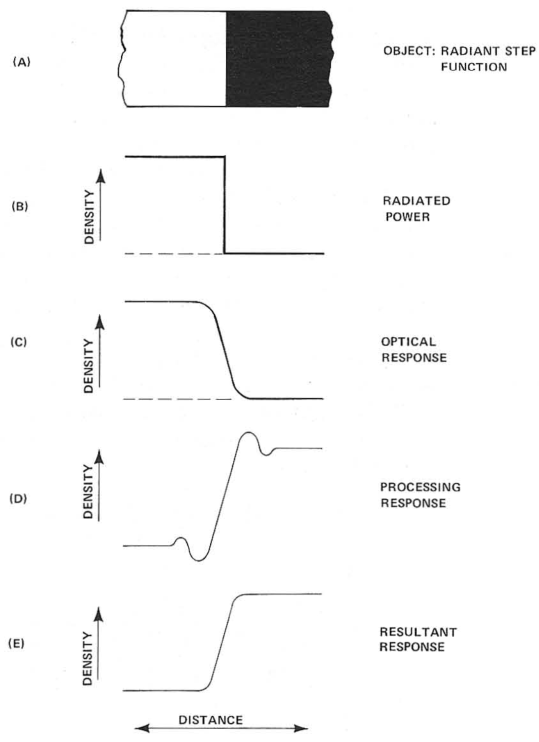


Fig. 3-19. Factors affecting edge response.

3.5. PROCESSING

conventional processing

Conventional photographic processing involves four discrete steps:

Development
Fixing
Washing
Drying

After reduction of exposed silver salts to silver molecules, the remaining silver halides are dissolved in the fixer solution and removed by the washing step. The drying step completes the hardening of the emulsion.

Commercial bulk processing machines carry the film through the requisite baths. The chemistry and temperatures are carefully controlled, and the process is automatic from load to unload, the film emerging completely dry. Chemistry is continually replenished as it is expended.

stabilization processing

Another quick development method is *stabilization* processing. Ordinarily the waste silver halides remaining after development are converted to water-soluble products and washed out of the photograph. To save the time and inconvenience of washing, the waste products can be stabilized, and rendered inert, providing excellent reproductions, but with limited keeping qualities. Stabilization systems provide a relatively simple machine which may even be hand cranked. The more useful systems are motor driven at a constant speed, and include film drying means. Charging the machine with developer and stabilizer is easily done, and the complete process can be handled by an unskilled person.

monobath processing

It is possible to process film in a single bath (monobath) consisting of developer and fixer, with good results, but the results cannot easily be controlled. Most diffusion-transfer reversal processing is done with a monobath in a sealed pod (Polaroid), as described in the next section.

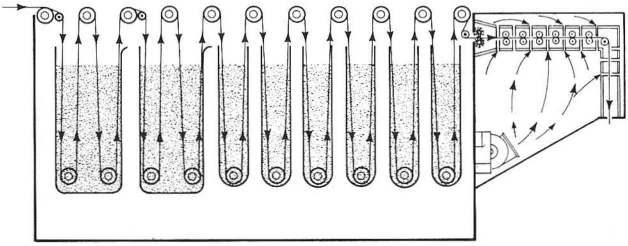


Fig. 3-20. Schematic of continuous flow processing.

3.6. DIFFUSION-TRANSFER REVERSAL*

criteria

For most oscillograph photography at this time the Polaroid process is most satisfactory. The criteria of film speed, contrast and resolution are adequate, the processing time and convenience are superior. The diffusion-transfer reversal process has been investigated since 1940, but was not of great commercial interest until Polaroid introduced a camera complete with processor in 1948.

process

Fig. 3-21 shows the general concept. If an ordinary-emulsion negative is exposed in the normal manner, and as soon as development has begun, the emulsion side is squeezed against a nonsensitized surface that carries available ions of silver, the unexposed silver-halides will diffuse into the surface of the positive and leave their silver on the surface where the particles of free silver of the original surface act as development centers.

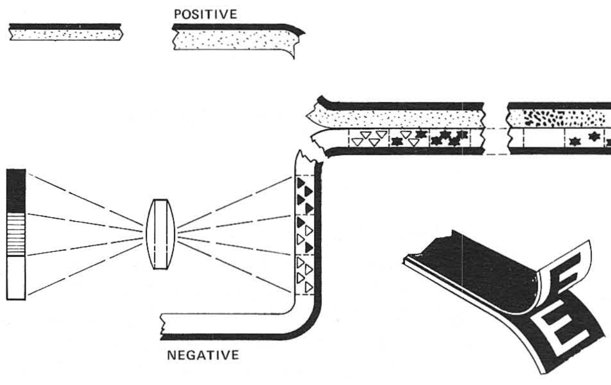


Fig. 3-21. Diffusion-transfer process.

advantages

The DTR process has potential for greater sensitivity because the image is on the surface of the negative only; a negative image of inadequate density for normal reproduction may be adequate for DTR. Also, the processing can be more violent because any processing fog is left on the negative; the positive does not pick up the fog. There is less loss of resolution because the two surfaces are in contact; there is less electron diffusion and little chance of film halation. The silver of the positive controls the particle size, rather than the grain of the negative, so grain is less evident in the print.

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*Ref: 27. Neblette, Ch 28
21(k). Kodak P-138

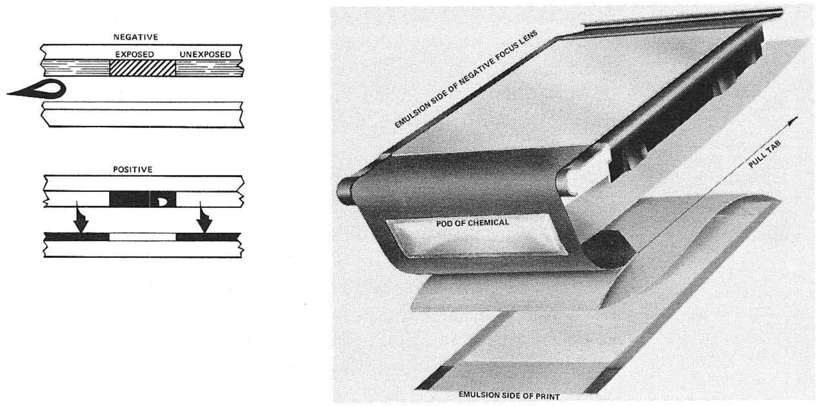

Fig. 3-22. DTR processing.

Polaroid[1]

The Polaroid negative is contained in one cavity, and the positive stock in another. Fixed to the print stock at appropriate intervals is a paper pod containing developer and fixer. The materials are so arranged that negative and positive are advanced together; pulling the tab starts the processing and pulls a new negative in place for exposure. After exposure, a pull on the tab draws negative and positive, emulsion to emulsion, through a set of rollers; the pod of processing gel is broken between the materials and the gel squeezed evenly over both surfaces (Fig. 3-22). After the processing period, from 10 to 60 seconds, depending on the type of film, the two pieces are stripped apart. The black and white prints are then hand-coated with varnish, supplied in an applicator. In most cases, the negative is discarded but some of the films make the negative available for more prints or enlargements.

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[1] Registered Trademark Polaroid Corporation

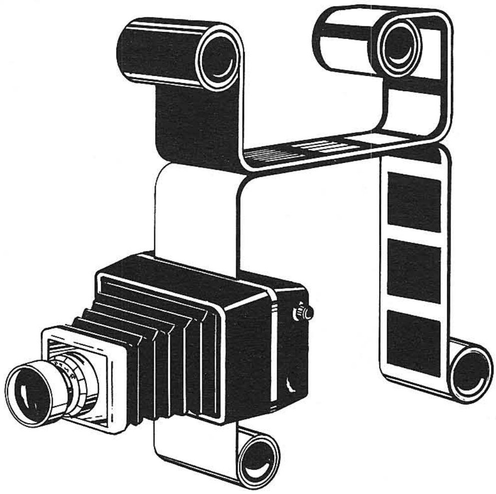
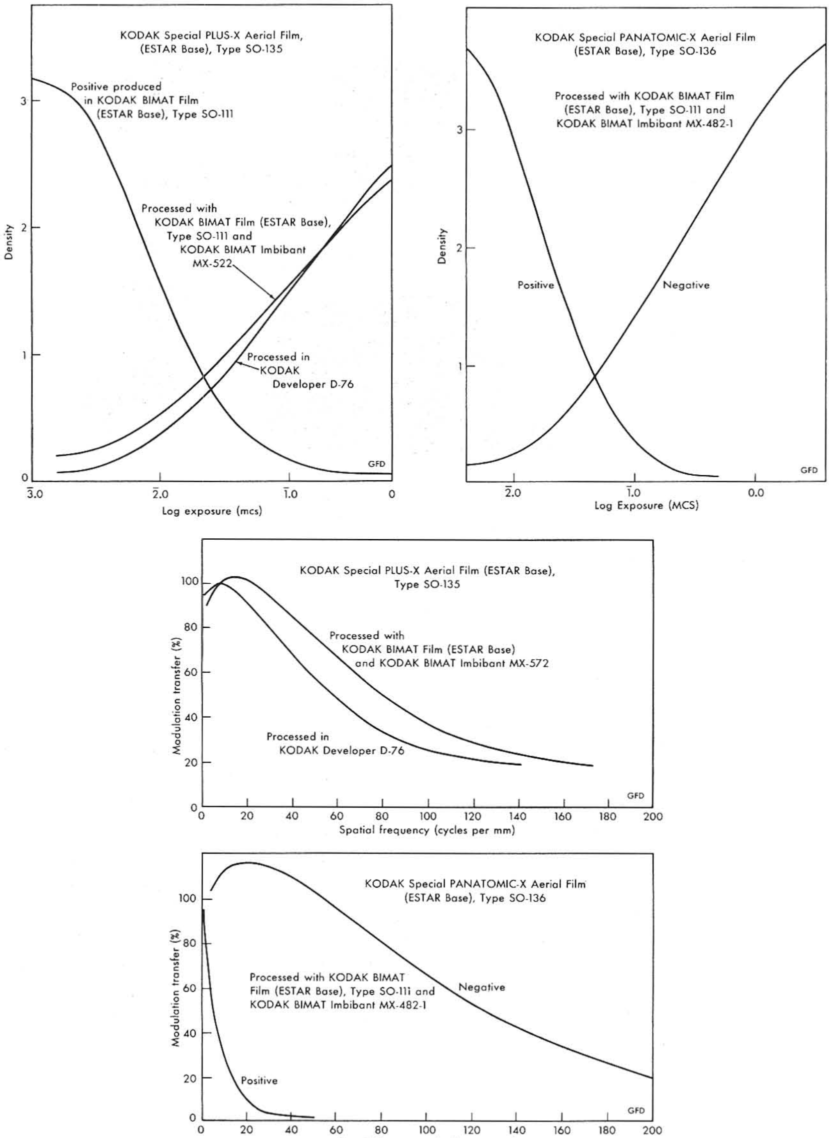


Fig. 3-23. Bimat processing.

Kodak Bimat[2]

Fig. 3-23 illustrates the Kodak Bimat process: A common negative film after exposure is squeezed together with the Bimat film for the prescribed development time; the negative is processed to a prescribed density and the positive Bimat is immediately available. For permanence, both films must be washed subsequently. The Bimat film consists of a base film and a coating of inactive gel. Before use, the film is soaked with a processing solution appropriate for the negative film being used. The gel swells as it soaks up the solution, but can then be stored under controlled temperatures for a reasonable period. Although the process is chemically wet, it is carried out without tanks or washes. Fig. 3-24 compares results of Bimat processing with those of the more usual methods.

[2] Registered Trademark Eastman Kodak Company



NOTE: Reproduced from a copyrighted Kodak publication.

Fig. 3-24. Film characteristics using Bimat processing.

3.7. DRY PROCESS MATERIAL (DRY SILVER)

Dry process materials were introduced to provide fast, convenient processing of black and white photocopy. The gel contains a relatively small quantity of silver halide, an image-forming silver soap and a developer. The latent image formed from the exposed silver halide acts as a catalyst when heated ($\approx 120°$ C), enabling the silver soap to be reduced to silver in the resulting image.

The process is fast and reasonably convenient, and the resolving power high. The greatest limitation at this time is the rather slow film speed, corresponding to the region of ASA 1. Dry silver paper is now being used effectively in a number of commercial applications.

3.8. OTHER PROCESSES*

diazo

The *diazo* process has been in use for many years in "blueprint" machines and is now used extensively in graphics processing and in microfilm duplication. The dye image of diazo provides very high resolution and can be processed in ambient light, but is too slow for oscilloscope applications.

vesicular

Vesicular film is also being used for microfilm reproduction. The image is formed by minute bubbles of nitrogen, released in the exposed area by heat processing. The bubbles scatter light, rather than absorbing it. The film may be slightly faster than diazo, but resolution is not as high.

electro-photography

Electrophotography depends on the characteristics of some materials to become conductive on exposure to light. An electrostatic charge previously applied will leak off in the exposed area and be retained in the dark area. A "toner," finely divided carbon particles, is attracted to the charged area and then fixed. Electrophotography is in the same sensitivity region as slow silver halide film. Many office copiers use this principle. Apparently, electrophotography would not provide any advantages for oscillograph recording.

Many other processes are being investigated but nothing to compete with the speed of silver halide has been announced.

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*Ref: 22. Kosar, Ch 6
27. Neblette, Ch 9

4

PHOTOGRAPHIC OPTICS

This chapter provides enough background for the individual to recognize physical characteristics of optical equipment used in general and oscilloscope photography and to evaluate performance to an approximation adequate for most applications. The background with the references will also provide a means for more serious study of optics.

The angles used to describe paths of light rays are usually measured from a line *normal* (perpendicular) to the surfaces being discussed.

4.1. REFRACTION*

index of refraction

In Chapter 2 we pointed out that the velocity of light in space is a fundamental constant. The velocity of light in other media is somewhat slower, depending on the molecular characteristics of the material. This difference in velocity provides an important principle of optics: *refraction*. The ratio of c, the velocity in space, to v_g, the velocity in a transparent medium g, is the *index of refraction, n*.

$$n = \frac{c}{v} \qquad \text{(Eq. 4-1)}$$

Because the velocity of light in air is so near to c, the index of refraction of air is usually considered to be unity, $n = 1$. The index for all other media is greater than one. By definition there can be no n less than one. For ordinary optical materials, n may range between 1.5 and 1.7.

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*Ref: 34. Southall, Ch 3
26. Monk, Ch 1, 2
18. Jenkins and White, Ch 1
14. Hardy and Perrin, Ch 2
27. Neblette, Ch 4

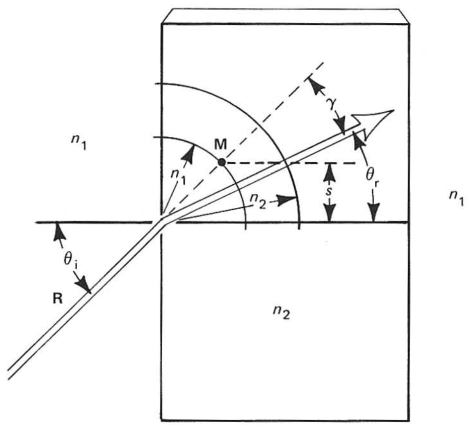

Fig. 4-1. Graphical solution of Snell's Law, $n_1 \sin \theta_i = n_2 \sin \theta_r$.

refraction angle

Fig. 4-1 shows a ray entering a transparent material at an angle to the normal, θ_i. Refraction causes the ray to deviate by an angle γ with respect to the original ray. The ray now makes an angle θ_r with the normal, equal to $\theta_i - \gamma$. If we know the index n_2 of the material, we can calculate the angle arithmetically or graphically by Snell's law:

$$n_1 \sin \theta_i = n_2 \sin \theta_r \qquad \text{(Eq. 4-2)}$$

$$\sin \theta_r = \frac{n_1 \sin \theta_i}{n_2}$$

if $n_1 = 1$, as in air,

$$\sin \theta_r = \frac{\sin \theta_i}{n_2}$$

graphical solution

Graphically, project R for a distance of n_1 units and lay a line parallel to the normal, through point M. Using a compass, strike an arc of radius n_2, through the line that passes through M. The new direction of R will pass through this intersection. If s is the distance from M to the normal, then

$$\sin \theta_i = \frac{s}{n_1}, \text{ and } \sin \theta_r = \frac{s}{n_2},$$

and $$n_1 \sin \theta_i = s = n_2 \sin \theta_r ,$$

and $$\sin \theta_r = \frac{n_1 \sin \theta_i}{n_2}$$

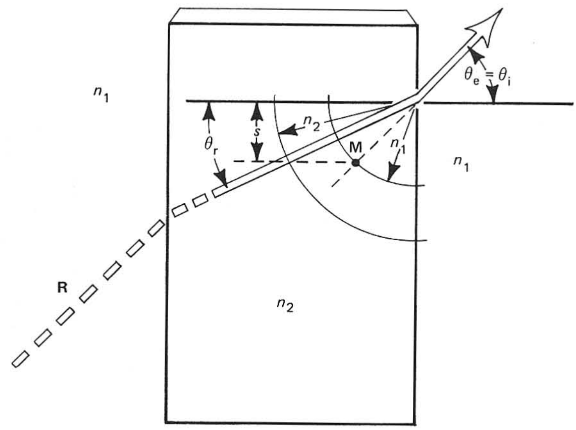

Fig. 4-2. Solution of Snell's Law going from dense to rare medium.

In a similar manner, the direction of the ray going from a dense medium to a less dense medium can be determined, as in Fig. 4-2.

4.2. MIRRORS*

image orientation

Confusion may arise in thinking about mirrors because of the sense of reversion of the image. The mirror reflects a scene with the same orientation as that of an observer behind the mirror. (The terms left and right are ambiguous.) A mirror merely shifts our point of observation by 180° in the same plane. The emulsion side of a film will orient a scene as though we were looking toward the camera from behind the scene. A scope display exposed directly on an opaque emulsion will provide a reversed record. A scope display reflected from a mirror before exposing a Polaroid print will provide a reversed record. The negative portion of a Polaroid image is reversed.

Fig. 4-3 illustrates the graphical solution of plane mirror problems. This method can be logically extended to multiple mirrors and image orientations. A good reference is Southall, Chapter 2.

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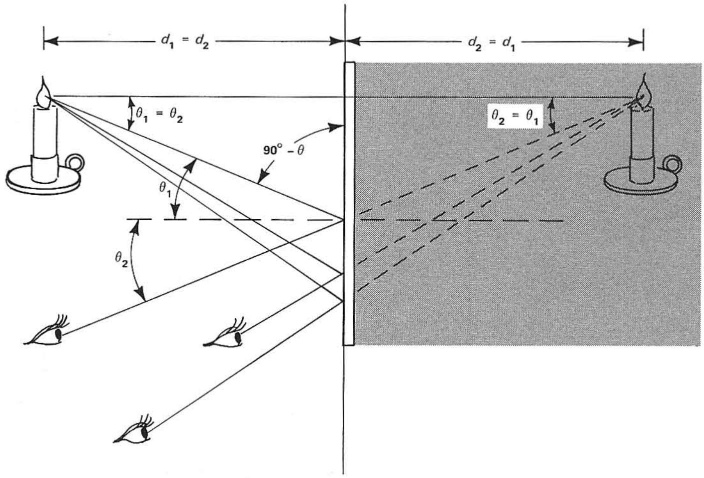
*Ref: 34. Southall, Ch 2
14. Hardy and Perrin, Ch 1
18. Jenkins and White, Ch 6



The angle of incidence, θ, is always measured from the normal, a line perpendicular to the reflecting surface.

Any ray striking the mirror at angle θ will be reflected at angle θ.

Fig. 4-3. Graphical solution of mirror problems.

A convenient device for remembering orientation from lens or mirror – look at an asymmetrical figure on a transparent sheet. A lens will rotate the figure 180° about a point in the center of the page; a mirror will rotate the figure 180° about an axis lying on the page from top to bottom, as illustrated in Fig. 4-4.

geometry of reflections

Light travels in straight lines in a homogenous medium, such as air at uniform temperature and pressure. It is reflected or refracted at planes of discontinuity of media, such as an air-to-glass or a glass-to-air interface. A plane specular surface reflects light at the same angle with the normal and in the same plane as the incident. This concept is extended to curved surfaces also, as shown in Fig. 4-5.

catadioptic systems

It is possible to build a lens system without refractive elements by using curved mirrors as lenses. Mirror lenses have none of those aberrations contributed by refraction; for example, there are no chromatic aberrations. More successfully, mirror lenses are combined with refractive lenses for astronomical work, such as the Schmidt telescope. These *catadioptic* systems are now being used as telephoto lenses for ordinary cameras because they are much shorter and lighter in weight with speeds on the order of f/1.0.

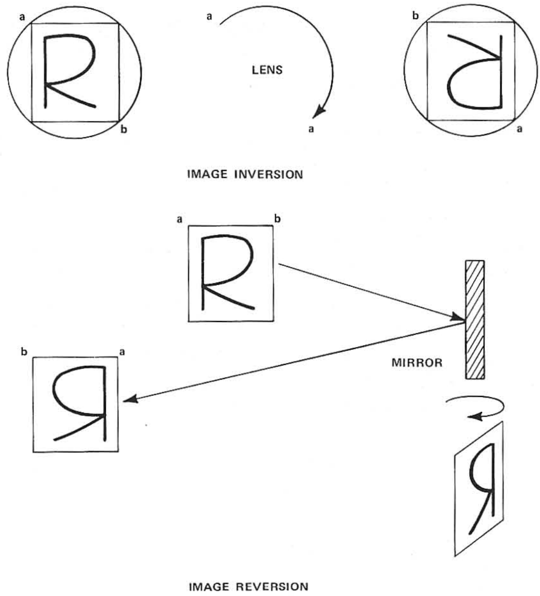
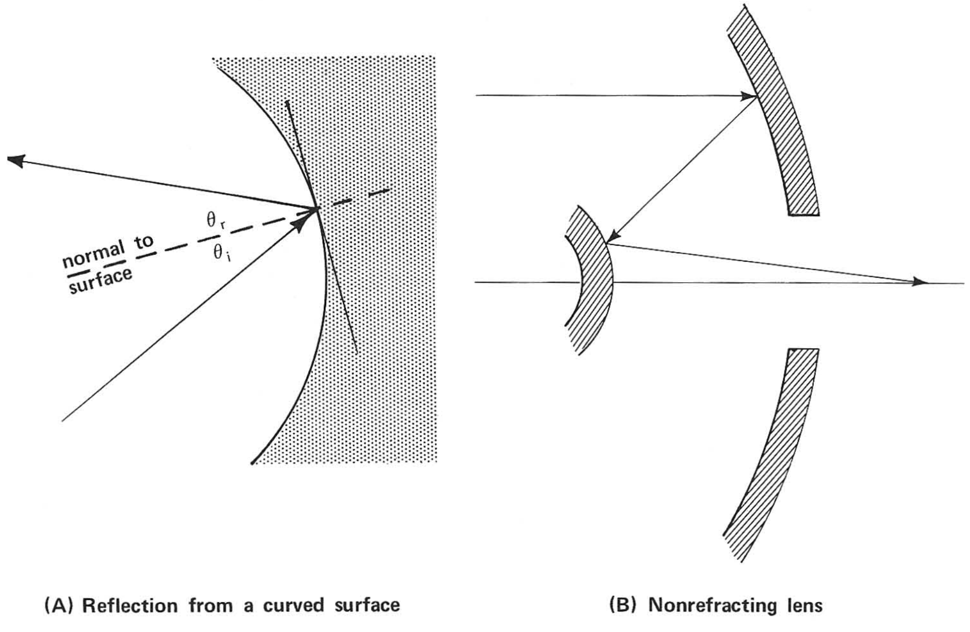


Fig. 4-4.



(A) Reflection from a curved surface **(B) Nonrefracting lens**

Fig. 4-5.

Fig. 4-6 illustrates some significant features of a simple optical device. (A) shows a cross section of the conventional household mirror; about 85% of the light is reflected from the silvered back; about 5% is reflected from the first surface; several percent is lost in the silvered backing, and some contributes to multiple reflections. A front-surface (or first-surface) mirror (B) absorbs a small percent

front surface

(<5%) of the light and reflects the rest; this is the mirror used in optical equipment. Another useful item is the beam-splitting mirror shown in (C); the first surface is lightly silvered to increase the reflectivity but allows part of the light to continue. As indicated in the diagram, multiple reflections occur, but can be inhibited to some extent by coating the surfaces. By using selective reflection

dichroic

coatings, the mirror may be made *dichroic*, reflecting light wavelengths from one end of the spectrum and transmitting light wavelengths at the other end.

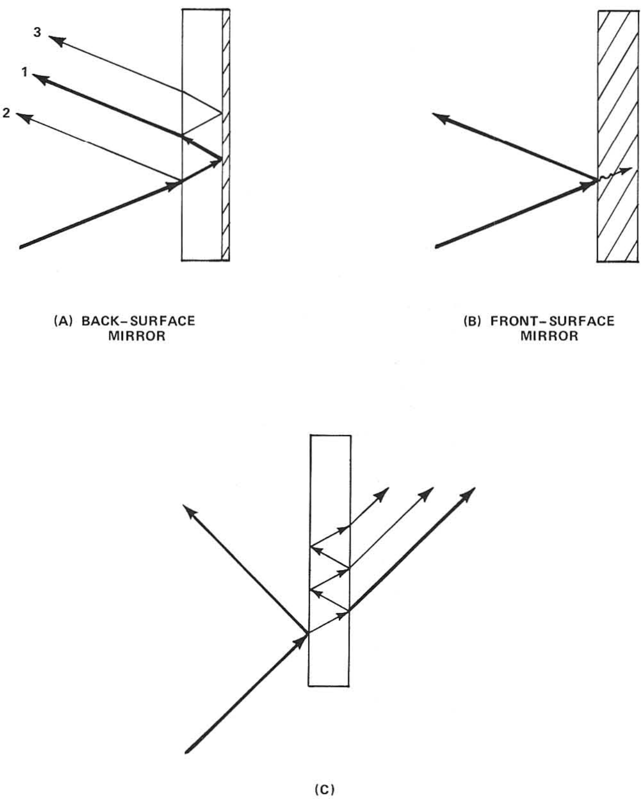


Fig. 4-6.

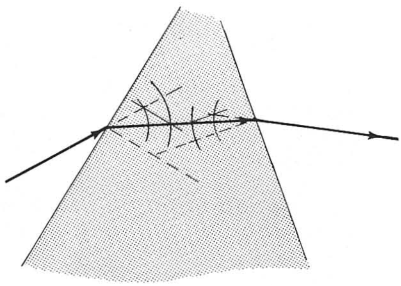


Fig. 4-7. Prism.

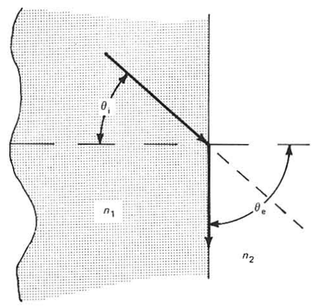


Fig. 4-8. Total reflection $\frac{\theta_e}{n_2}$.

4.3. PRISMS*

When two plane surfaces bounding a medium in the optical path are not parallel, as in Fig. 4-7, the ray leaves the glass at a different angle than that of the incident; the device is a *prism*. Prisms perform a number of optical functions, but their use as refraction devices is limited because of the difficult problem of correcting *dispersion*, resulting from the difference in index of refraction of a medium for different wavelengths.

The index is usually quoted at the wavelength of the yellow sodium line, 589 nanometers. The index at other wavelengths will differ by a fraction of a percent. These slight differences in index account for the display of the visible spectrum effected by sunlight through a prism.

Prisms are often used as a system of first-surface mirrors, where reflections occur from inside faces of a three-dimensional body.

total reflection

The principle of *total reflection* is significant in the use of prisms and fiber optics. The ray emerging from the dense medium into air makes an angle θ_e with the normal, where $n_1 \sin \theta_i = n_2 \sin \theta_e$. When θ_e becomes 90°, as in Fig. 4-8, all the light is reflected and no light from the ray emerges from the glass. It is evident from the equation that when θ_e becomes 90°, $\sin \theta_e = 1$, and $\sin \theta_i = n_2/n_1$. When n_2 is *one*, as in air,

critical angle

$$\sin \theta_i = 1/n_1 \text{ and } \theta_i = \theta_c, \text{ the } \textit{critical angle} \qquad \text{(Eq. 4-3)}$$

The critical angle depends only on the index of refraction of the glass for a glass-to-air device. A straight glass rod acts as a light pipe for all rays entering at greater than the critical angle. This leads us, later on, to fiber optics.

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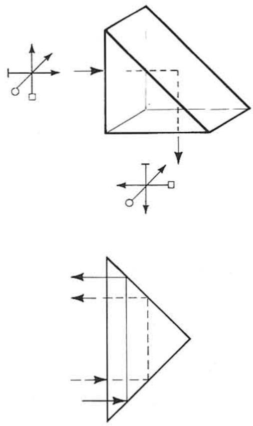
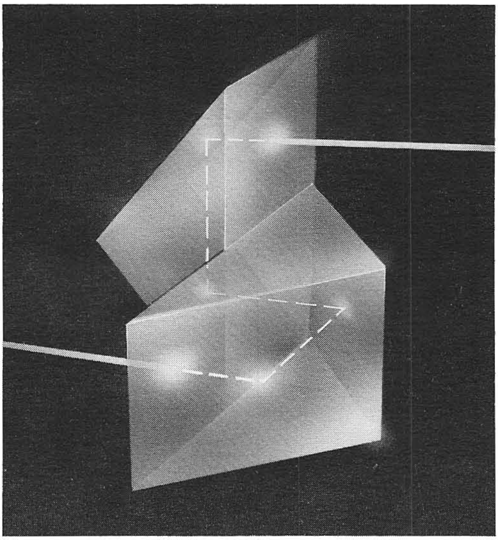
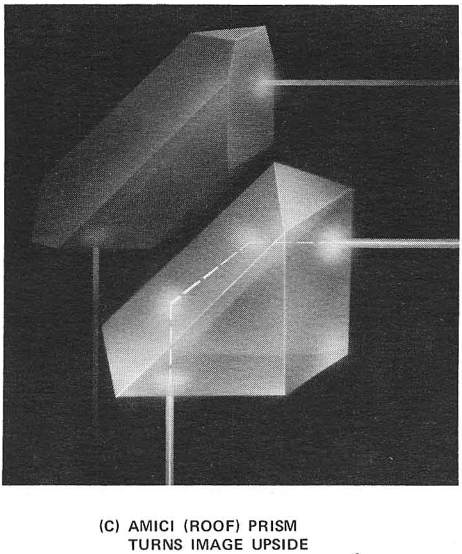
*Ref: 34. Southall, Ch 5
26. Monk, Ch 8
18. Jenkins and White, Ch 1
17. Jacobs, Ch 11



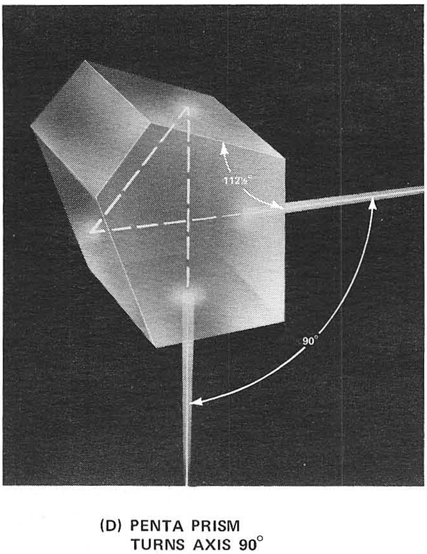
(A) RIGHT-ANGLE PRISM



(B) PORRO PRISM
FOR BINOCULAR



(C) AMICI (ROOF) PRISM
TURNS IMAGE UPSIDE
DOWN AND TURNS AXIS 90°



(D) PENTA PRISM
TURNS AXIS 90°
IMAGE REMAINS
ERECT AND CORRECT

Fig. 4-9.

prism configurations

Fig. 4-9 illustrates a number of reflecting prisms, showing orientation of the reflections. The tails on the arrows help determine which dimensions are reversed. The first four prisms in the diagram do not refract the light because all rays are paraxial; they enter and depart normal to the glass surface. For this reason there is no dispersion (of color) to be corrected. All the deviations are in multiples of 90°. All the inversions and reversions can be inferred by considering the prism a system of fixed mirrors. The *Porro prism*, set up as right-angle pair (*B*), is used to erect the image in binoculars.

Porro prism

penta prism

The *penta prism* (*D*) is important in rangefinders; by adding a roof, it provides the eye-level viewfinder/rangefinder used in many 35-mm single-lens-reflex cameras. Fig. 4-10 illustrates the inversions and reversions occuring from object to eye. The lens rotates the image about the optical axis and the mirror erects the image, but rotates it about its vertical axis. The image must now be diverted by 90°, rotated again about the optical axis and about its vertical axis. The advantage of all the extra manipulation is evident to anyone who has tried using a single-mirror reflex camera in other than camera-normal position.

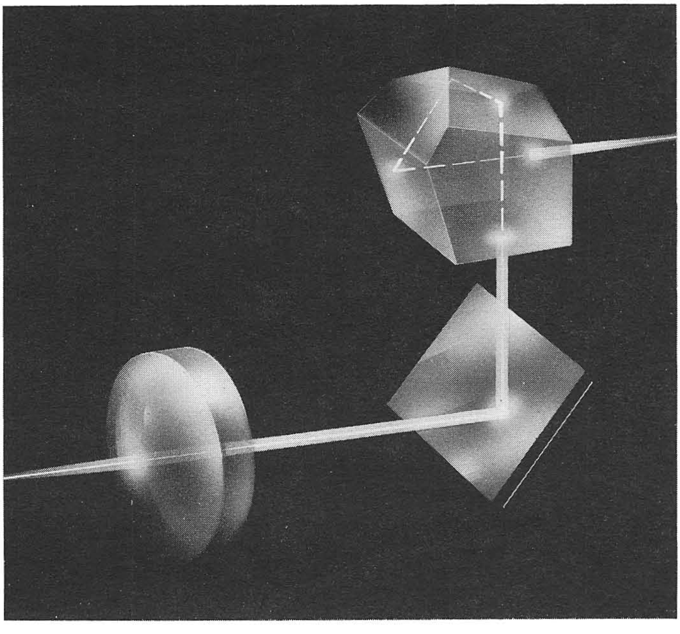


Fig. 4-10. Pentaprism with roof.

Dove prism

The *Dove prism*, Fig. 4-11, uses the principles of refraction and of total reflection. The image is rotated about the optical axis. If the prism is rotated about its optical axis, the image will rotate through twice the angle of rotation of the prism. The device has application in viewfinders and in constant-erection rotating devices and for image reverting.

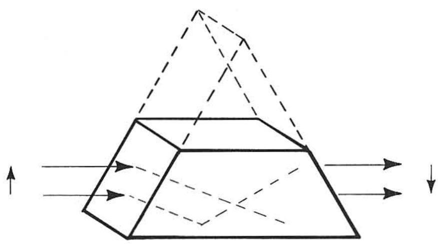


Fig. 4-11. Dove prism. Image rotates through twice the angle of axial prism rotation.

4.4. FIBER OPTICS*

Fig. 4-12A represents a plane cut through a cylindrical section of optical material having smooth, polished boundaries.

critical angle

The figure traces the paths of the several rays, *a*, *b* and *d*. Ray *a* enters at angle θ_1 with the axis, and is refracted by the glass: $\sin\theta_2 = n_1 \sin\theta_1/n_2$. The ray strikes the wall at an angle $\phi_2 = 90° - \theta_2$. For ray *a*, $\sin\theta_2 > n_1/n_2$; ϕ_2 is greater than the critical angle and none of the energy will be refracted through the wall. Almost all the energy will be reflected and continue to strike the wall at angle ϕ_2 to the end of the piece, and leave at the same angle at which it entered, according to the optical geometry shown. Ray *b* strikes the top surface at an angle less than the critical angle, $\arcsin n_1/n_2$. In this case the medium outside the glass is air, and $\sin\phi_c = 1/n_2$. Light can escape at all angles less than ϕ_c, but is trapped at angles greater than ϕ_c.

Ray *d* strikes the top face at an angle to the normal greater than ϕ_c, and is reflected, but the angle it makes with the axis is also greater than ϕ_c, and so it is reflected again from the end face.

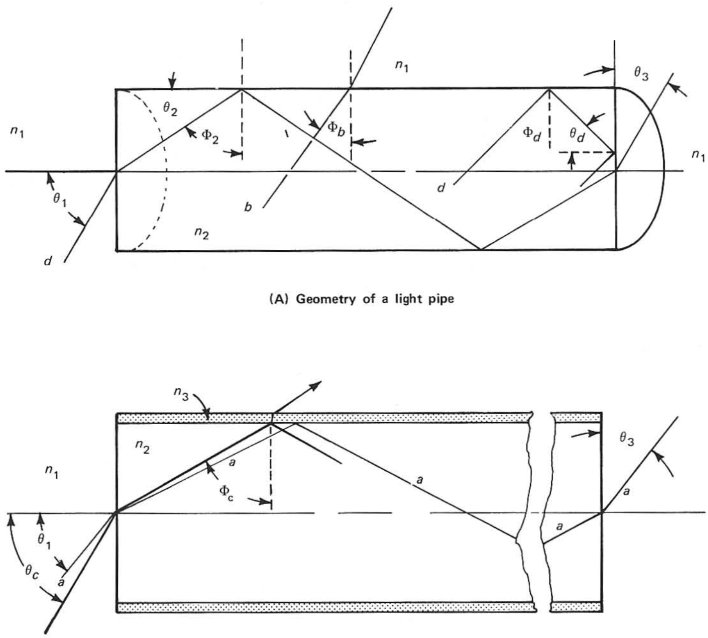
*Ref: 20. Kapany

light pipe

A *light pipe* is usually cylindrical; entering rays that do not pass through the axis (skew rays) trace a helical path, but most of the rays leave the pipe at the same angle at which they entered.

fiber bundle

The glass cylinders can be small enough to be very flexible, as fibers, and cabled together so that each pipe maintains its position throughout the length of the cable. An image focused on one end will appear at the other end; the resolution of the second image will depend on the number of fibers in the bundle.



(A) Geometry of a light pipe

(B) Geometry of fiber optics

Fig. 4-12.

4.5. LENS DEVELOPMENT*

The following principles are presented for background on lenses in general. A few of many texts on optics are listed that provide detailed developments of optical principles. Hardy and Perrin, *Principles of Optics*, was used as a guide.

In a study of optical *surfaces*, a discipline of signs must be used to translate the graphics into equations. The following will be used:

optical ground rules

1. Light originates on the left of the diagram.
2. *Object distance u* is positive when the object is to the left of the *vertex*, the point where the optical surface crosses the axis.
3. *Image distance v* is positive when the image is to the right of the vertex.
4. Radius of curvature is positive when the center of curvature is to the right of the vertex.
5. A distance measured *up* from the axis is positive.

Fig. 4-13 illustrates a chunk of optical material of index n_1 with a smooth spherical surface of radius r_1. The material outside is air, with index $n = 1$. Then:

$$\frac{n_1}{v_1} + \frac{1}{u_1} = \frac{n_1 - 1}{r_1} \qquad \text{(Eq. 4-4)}$$

Fig. 4-14 adds the second surface to Fig. 4-13. The second surface provides:

$\dfrac{n_1}{u_2} + \dfrac{1}{v_2} = \dfrac{1 - n_1}{r_2}$, and if the lens thickness is small with respect to v_1 and u_2, $u_2 = -v_1$, and

$\dfrac{n_1}{-v_1} + \dfrac{1}{v_2} = \dfrac{1 - n_1}{r_2}$. Adding this to Eq. 4-4 provides

$$\frac{1}{u_1} + \frac{1}{v_2} = (n_1 - 1)\left(\frac{1}{r_1} - \frac{1}{r_2}\right). \qquad \text{(Eq. 4-5)}$$

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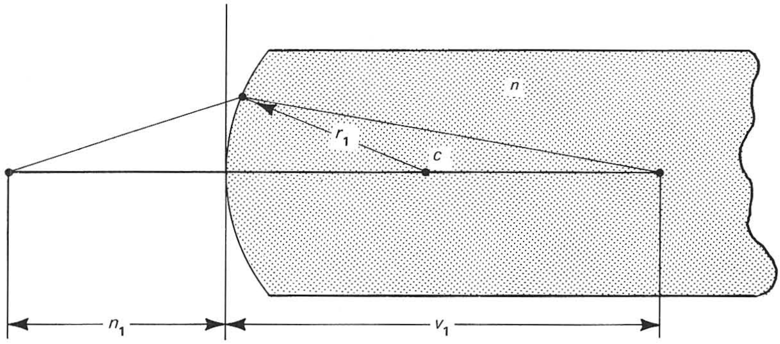
*Ref: 34. Southall, Ch 6, 7
26. Monk, Ch 1
18. Jenkins and White, Ch 3, 4, 5
14. Hardy and Perrin, Ch 2, 3, 4



$$\frac{1}{u_1} + \frac{n}{v_1} = \frac{n-1}{r}$$

Fig. 4-13. Geometry of an optical surface.

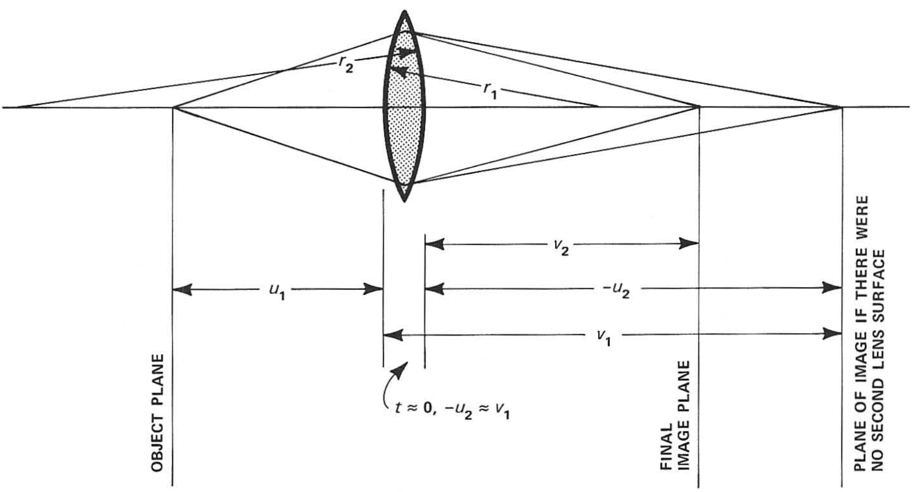


Fig. 4-14. Geometry of lens surfaces.

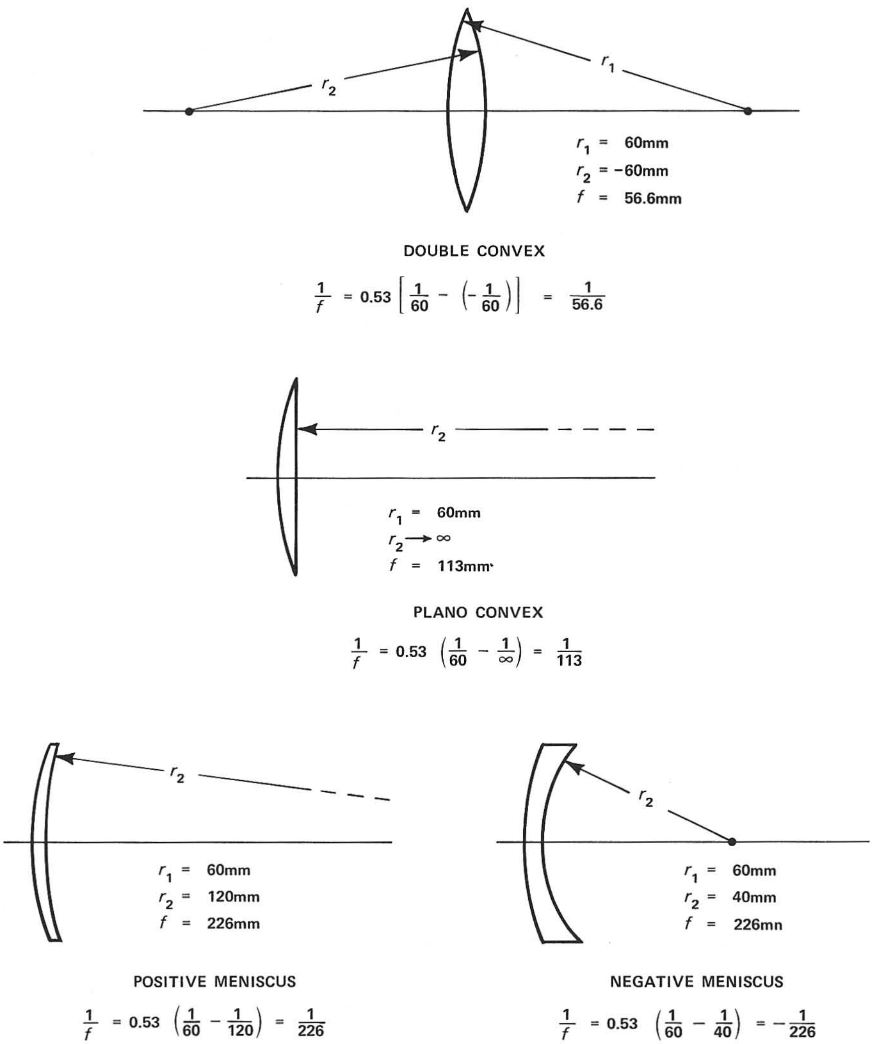


Fig. 4-15. Examples of lens *shapes.*

focal length

To appreciate the relationship of surface curvature to lens focal length, notice in Fig. 4-15 the following examples: The first surface has a radius r_1 = 60 mm in all cases, and the index of refraction is $n = 1.53$. Lens thickness is neglected.

The expression for the relationship of conjugate distance to focal length, illustrated in Fig. 4-18, is:

$$\frac{1}{f} = \frac{1}{u} + \frac{1}{v},$$

Then:

$$\frac{1}{f} = (n_1 - 1)\left(\frac{1}{r_1} - \frac{1}{r_2}\right), \qquad \text{(Eq. 4-6)}$$

where n_1 = index of lens material
r_1 = radius of first surface
r_2 = radius of second surface
f = focal length, and
thickness of lens is small compared to f.

The calculations in Fig. 4-15 are too gross for design procedures; the illustrations provide a sense of relationships.

diopters

Note that Eq. 4-6 expresses the *power* of the lens in *diopters*, when dimensions are in meters. When dimensions are in millimeters, multiply the expression by 1000:

$$\text{Power in diopters, } D = \frac{1000}{f_{mm}}$$

curvature equals $\frac{1}{r}$

If the radius terms in Eq. 4-6 are replaced by the equivalent curvatures, where $c = \frac{1}{r}$, then

$$\frac{1}{f} = (n - 1)(c_1 - c_2) \qquad \text{(Eq. 4-7)}$$

Development of the lens shapes of Fig. 4-16 from Eq. 4-7 reveals that any number of shapes may be designed to the same focal length. This option is used to tailor the individual shapes of a lens system to correct for several lens aberrations as noted in Fig. 4-36.

converging and diverging lenses

Most single lenses we see are thicker in the center than at the edge and are termed *positive* or *converging* lenses. Lenses that are thicker at the edge are termed *negative* or *diverging* lenses (Fig. 4-17).

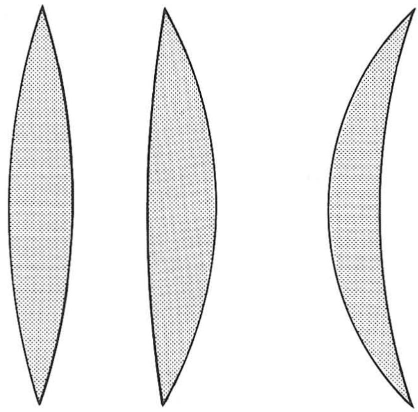


Fig. 4-16. Lens shapes with equal focal lengths.

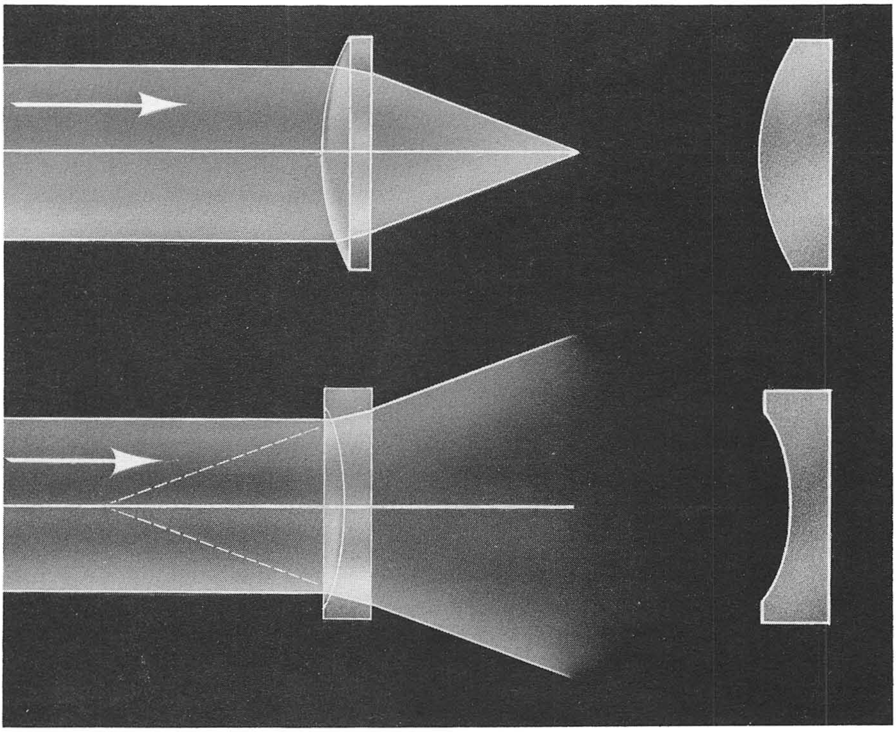


Fig. 4-17. Positive and negative lenses.

4.6. CONJUGATES*

back focal length

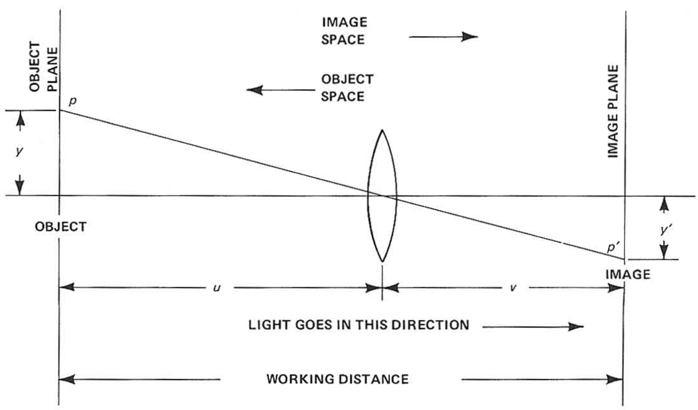
Light coming from a point distant enough that the rays are parallel will focus at F, the *back focal point*. The distance from the plane of a thin lens to F is the focal length f of the lens. If the plane of the lens is tilted through a small angle, without lateral shift, the distant point will remain focused at F. If a physical plane, such as a ground glass plate, is fixed at F, normal to the axis, a distant object will be imaged in the plane, inverted. If the object distance is 1000 X f, the image height will be 1/1000 (precisely, 1/999) of the object height. This is a *real image*.

real image

virtual image

The image formed by the diverging lens at F in the lower figure is a *virtual image*. It can be viewed from behind the lens, but cannot be displayed on a surface. Fig. 4-18 shows the conjugate relationship of u and v:

$$\frac{1}{f} = \frac{1}{u} + \frac{1}{v}. \qquad \text{(Eq. 4-8)}$$



$$\frac{1}{f} = \frac{1}{u} + \frac{1}{v};\ f = \frac{uv}{u+v}$$

$$M = \frac{y'}{y} = \frac{v}{u}$$

$$v = f(M + 1)$$

$$u = f(1 + 1/M)$$

$$^{*}WD = u + v = f(2 + M + 1/M)$$

*This is true only for a thin lens; an approximation for working lenses.

Fig. 4-18. Thin-lens conjugate equations.

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*Ref: 14. Hardy and Perrin, Ch 3

magnification

Note in Fig. 4-18 the rays shown trace only light travelling from p to p'. The light from p is gathered by the whole effective surface of the lens. The light from every illuminated point of the object passes through the lens in the same manner. From the geometry of Fig. 4-18, it can easily be inferred that the image-to-object ratio, or magnification, is $y'/y = v/u$.

$$M = \frac{v}{u} \qquad \text{(Eq. 4-9)}$$

working distance

The distance between the object plane and the image plane is the *working distance, WD*. For a *thin lens* the sum of the conjugates $u + v = WD$. For any given focal length, u will have a particular value for every value of v; this relationship is plotted in Fig. 4-19.

$$\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$$

two lenses

If two thin lenses are separated by a distance a (Fig. 4-20), the focal length of the combination will be:

$$\frac{1}{f_0} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{a}{f_1 f_2}, \text{ and}$$

$$f_0 = \frac{f_1 f_2}{f_1 + f_2 - a} \qquad \text{(Eq. 4-10)}$$

If the lenses are touching, and a becomes zero,

$$f_0 = \frac{f_1 f_2}{f_1 + f_2}, \text{ and if } f_1 = f_2, \qquad \text{(Eq. 4-11)}$$

$$f_0 = \frac{f}{2}$$

effective focal length

The first characteristic of the lens system we need to know is the *effective focal length, f*. This factor cannot be measured mechanically on a lens system but must be measured optically.

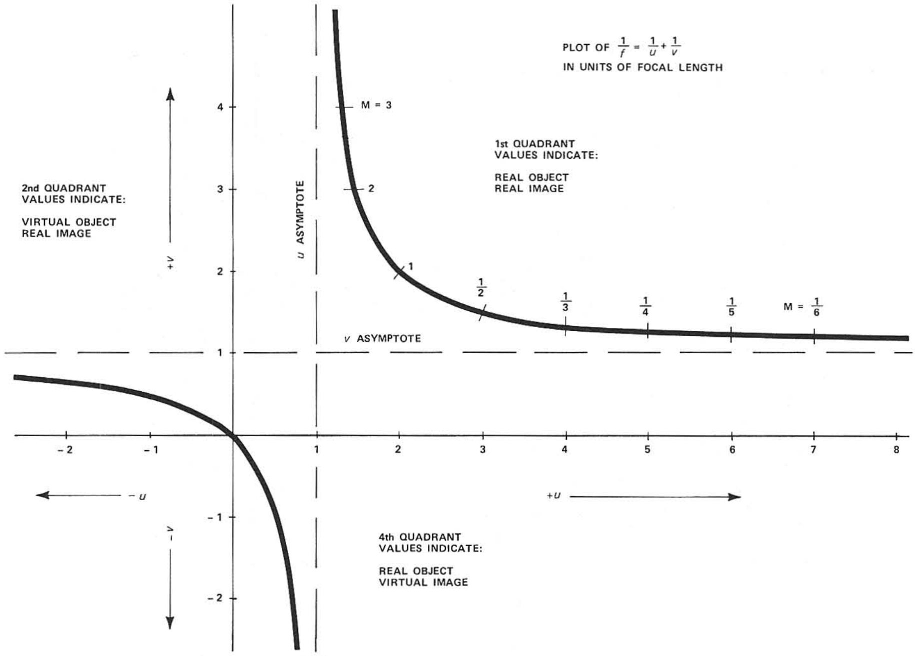

Fig. 4-19. Graph of conjugates vs magnification, M.

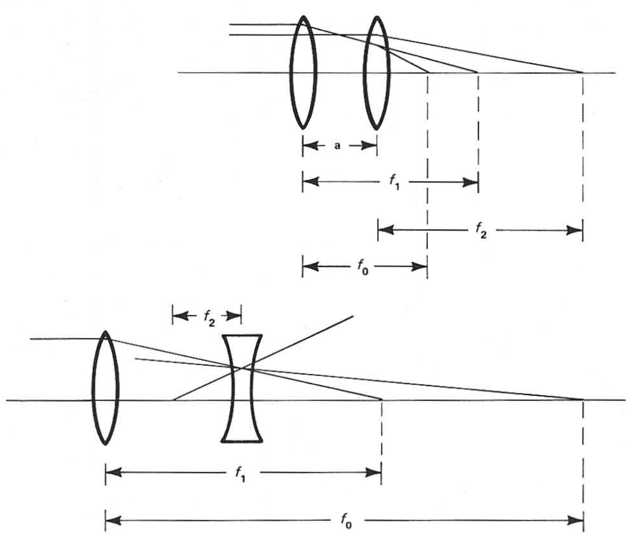

Fig. 4-20. Focal length of two lenses.

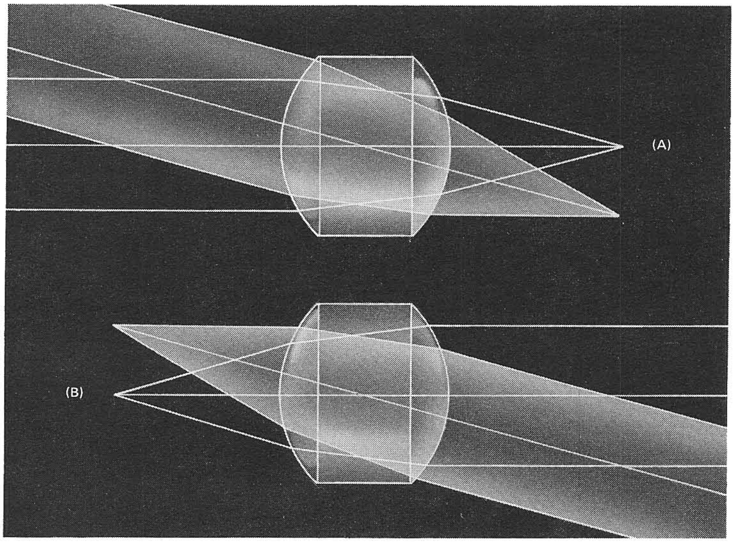

Fig. 4-21. Front and rear focal plane.

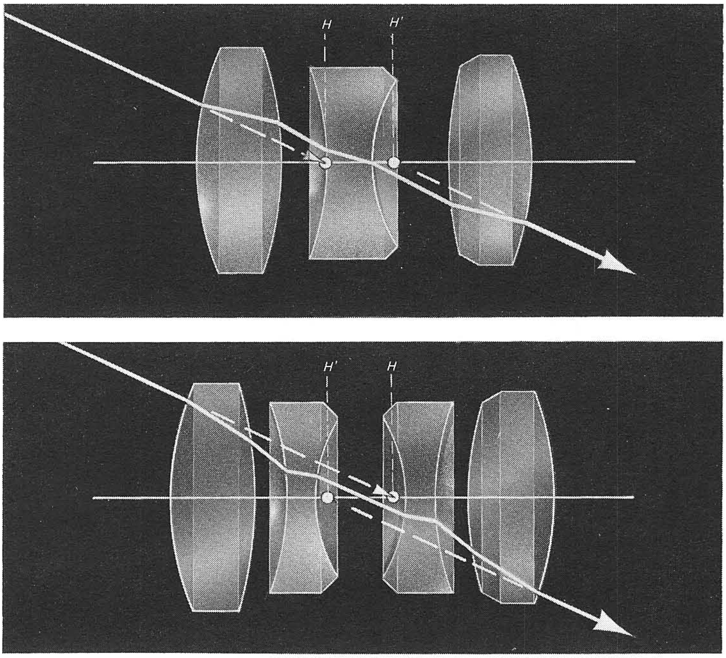

Fig. 4-22. Location of nodal points.

rear focal plane
rear focal point

If the light comes from a point at infinite distance, the rays will be parallel as they enter the lens. They will focus on the *rear focal plane.* If they enter parallel to the lens axis, they will focus at the *rear focal point* in Fig. 4-21A.

infinite distance versus infinity

Some confusion may arise from the terms *infinite distance* and *infinity*. A source of light at an infinite distance will have zero dimensions at the image plane no matter how large it may be. An object at "infinity" focus has finite dimensions at the image plane; it is not a point source but is composed of an infinite number of point sources.

If the point of light is moved toward the lens until the rays leaving the lens are parallel, the point will lie on the *front focal plane*, Fig. 4-21B.

4.7. PRINCIPAL POINTS*

nodal points
principal planes

There are two important reference points in a lens system, the *nodal points*, to which nearly all optical distances are referred. The nodal points are identical to *principal points* in any system where air is the medium at both ends of the system. *H* and *H'* are *principal planes.*

Any entering ray that passes through the front nodal point will leave the rear nodal point at the same angle. Note well! Both nodal points are not always "inside" the lens system, and the front nodal point may be *behind* the rear nodal point. The location of the nodal points is defined by the design of the system; see Fig. 4-22.

In Fig. 4-22 the lines drawn through the nodal points represent the principal planes, *H* and *H'*. These are reference planes for optical distances. We can represent the lens system in stylized form if we are not concerned about the arrangements of the lens *elements*, the individual pieces of glass. Fig. 4-23 illustrates some of the lens characteristics we need to know.

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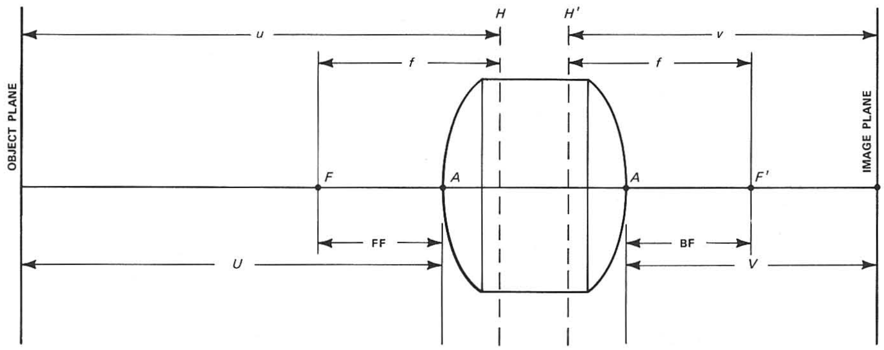
*Ref: 14. Hardy and Perrin, Ch 4



A	VERTEX OF LENS	*f*	FOCAL LENGTH (EFL, EFFECTIVE FOCAL LENGTH)
u	OBJECT DISTANCE	*H*	FIRST PRINCIPAL PLANE
v	IMAGE DISTANCE	*H'*	SECOND PRINCIPAL PLANE
F; *F'*	FOCAL POINTS	*U*	FRONT CONJUGATE
FF	FRONT FOCUS	*V*	BACK CONJUGATE
BF	BACK FOCUS		

The vertex *A* is the point defined by the axis and the outer surface of the lens.

The position of the principal planes may be reversed.

The points defined by the axis and the principal planes are nodal points in an air-glass-air system.

Fig. 4-23. Important lens dimensions.

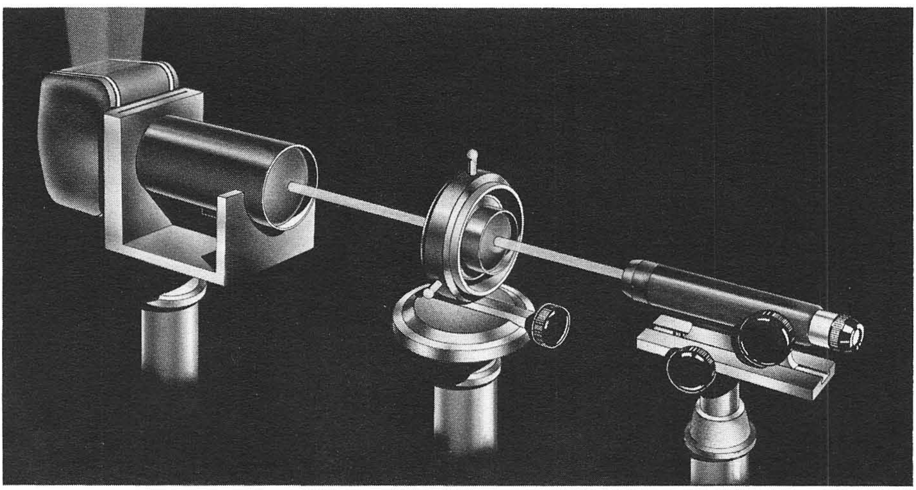


Fig. 4-24. Optical bench.

The distance from the front focal plane F to the first principal plane H is always equal to the distance between H' and F'; this is the *focal length* of the lens, f. A point in the *object plane* will be focused in the *image plane*. The object distance u and the image distance v are the *conjugates*. They are now measured to the principal planes as indicated, and $\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$. But with this lens system u and v cannot be measured directly because the nodal points cannot be located directly, but must be measured optically.

4.8. OPTICAL MEASUREMENTS*

optical bench

Measurements of lens characteristics are made on an optical bench, which may be a rudimentary arrangement or purchased for several thousand dollars, depending on the accuracy required. A simple optical bench, Fig. 4-24, consists of a source of light, a target and collimator; ways along which the *nodal slide* travels, and a viewing telescope, or a ground-glass screen.

If the light from the target is collimated, that is, the rays are parallel, it appears to come from an infinite distance. The light that passes through the lens will be focused precisely at the focal length of the lens. Focal length is the distance between the focal point and the corresponding principal point; for a lens infinitely thin, the principal point must be on the axis in the plane of the lens.

nodal slide

The *nodal slide* consists of a base that slides parallel to the light beam, a platform mounted to the base by a pivot in the center of the base, and a lens holder that can be slid axially along the platform. The center of the pivot axis is referenced to a scale at the edge of the optical bench (Fig. 4-25A).

finding the nodal points

To find the nodal points after the lens is set up in the holder, the target is imaged on the ground glass or in the telescope (Fig. 4-25B). The lens is pivoted to check the amount of image shift. Then the lens is shifted with respect to the pivot point; the telescope or ground glass is repositioned to correct the focus, and the assembly is again pivoted. The process is continued until the point is found where the image does not shift as the assembly is pivoted; this point is the second nodal point (principal point). A ray leaves the second nodal point parallel to the ray entering the first nodal point, consequently the image will not shift as the lens pivots about the second nodal point.

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*Ref: 26. Monk, p 343

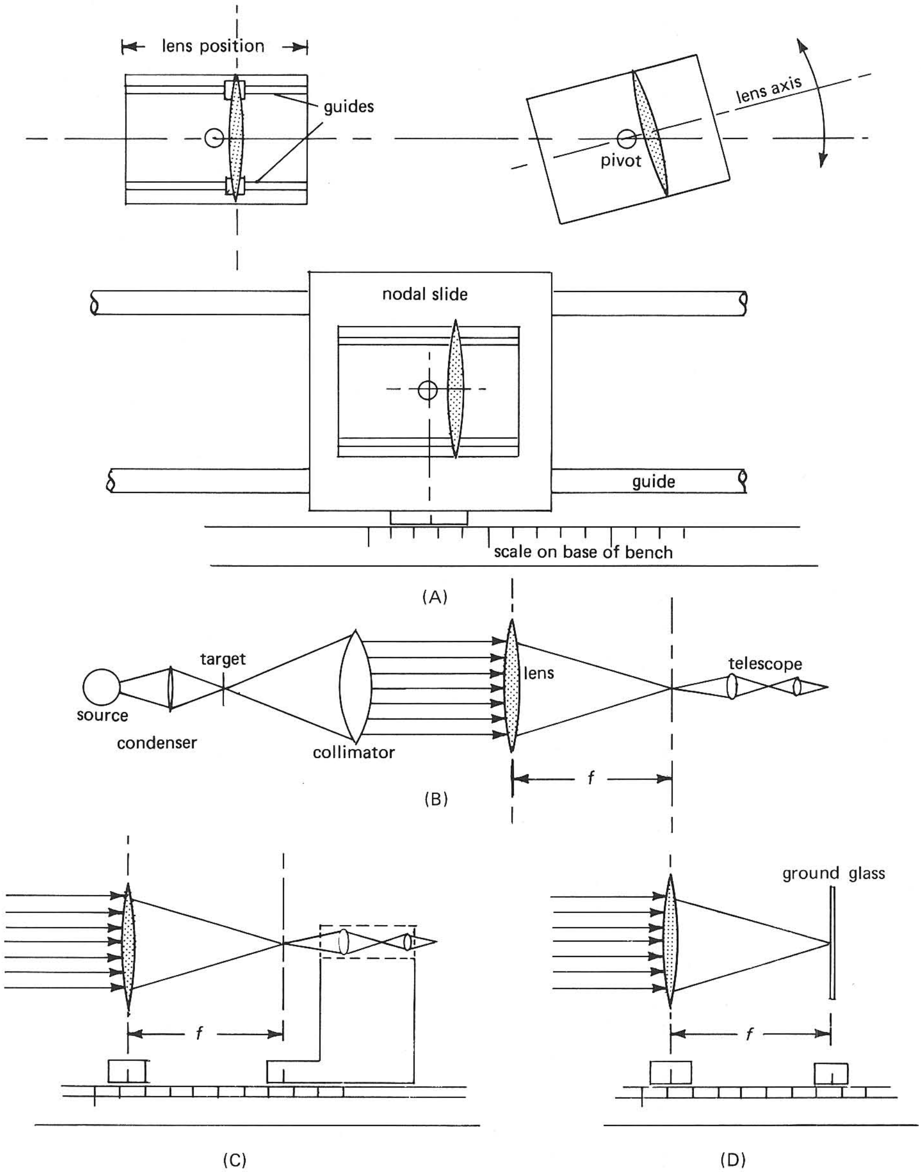

Fig. 4-25. Nodal slide.

When the nodal point has been found and the telescope focused, measure off on the bench scale the distance between the second nodal point and the point where the image was focused in the telescope. This is the focal length, f, Figs. 4-25C and D. The first nodal point is found by reversing the lens and repeating the procedure.

After a nodal point has been found, a mechanical reference to the vertex of the lens can be established by making a visible mark on the surface of the lens at the vertex, and bringing the telescope toward the lens until the mark is in focus. The distance from the nodal point to the vertex can then be read off the scale. Other useful optical distances can then be calculated or measured physically (see Fig. 4-23A).

depth of field

Depth of field defines the range of distance from the lens over which objects will be in focus on the image plane.

field of view

The edges of the focused image, projected through the system toward the object, define the *field of view*. The *field angle* is the plane angle subtended by thc boundaries of the imaged object. A *field stop* masks the edges of the image; its opening may be shaped in any geometrical figure. The field of view may be limited by the field angle, or by the field stop (Fig. 4-26).

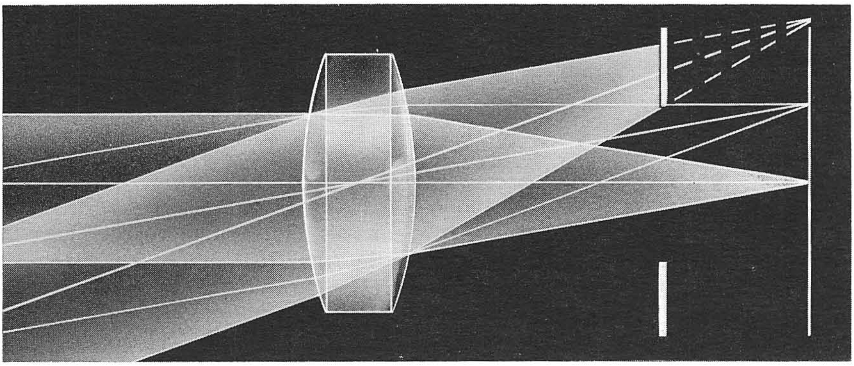

Fig. 4-26. Field of view.

4.9. STOPS AND APERTURES*

A *stop* in an optical system is an opaque sheet with a hole (aperture) of a proper size to limit certain light rays; stops are used for various purposes. Important to us is the *f*-stop (*aperture stop*), which permits control of the amount of light passing through the lens. Usually, *f*-stops are adjustable, and placed at a critical point between elements of the lens. A calibrated control is provided, and when the shutter is open, the effect of adjustment can be observed. If you have a single-lens reflex camera, or one with a ground-glass focus plate, you can observe how the light diminishes as the lens is "stopped down" and also how much more of the image appears to be in focus.

f-stop (aperture stop)

In Fig. 4-27A, S is an aperture stop between two lenses. S limits the beam between A and B, and D_n is the image of stop S as seen from p. Also, D_x is the image of S as seen from p'.

entrance and exit pupils

D_n as seen from p is the *entrance pupil*; D_x as seen from p' is the *exit pupil*. Fig. 4-27B is scaled from an actual lens, showing entrance and exit pupils.

relative aperture

The *relative aperture* of a lens is focal length f, divided by diameter of the entrance pupil, D_n:

$$f\text{-number} = \frac{f}{D_n} \qquad \text{(Eq. 4-12)}$$

and

$$\frac{f}{D_n} = \frac{1}{2 \sin \theta}$$

circles of confusion

Fig. 4-28 shows a lens with point A focused on the image plane. Point B, closer to the lens, focuses beyond the image plane, at B′. Points distant from the lens, from which the light rays appear parallel, will focus at the rear focal point, F_2. The rays from point B form a cone that is cut by the image plane at A′, imaging a circle rather than a point. Distant rays focus at F_2. A section of this cone also is imaged at A as a circle. These circles are *circles of confusion*, and their diameter limits resolution of the image.

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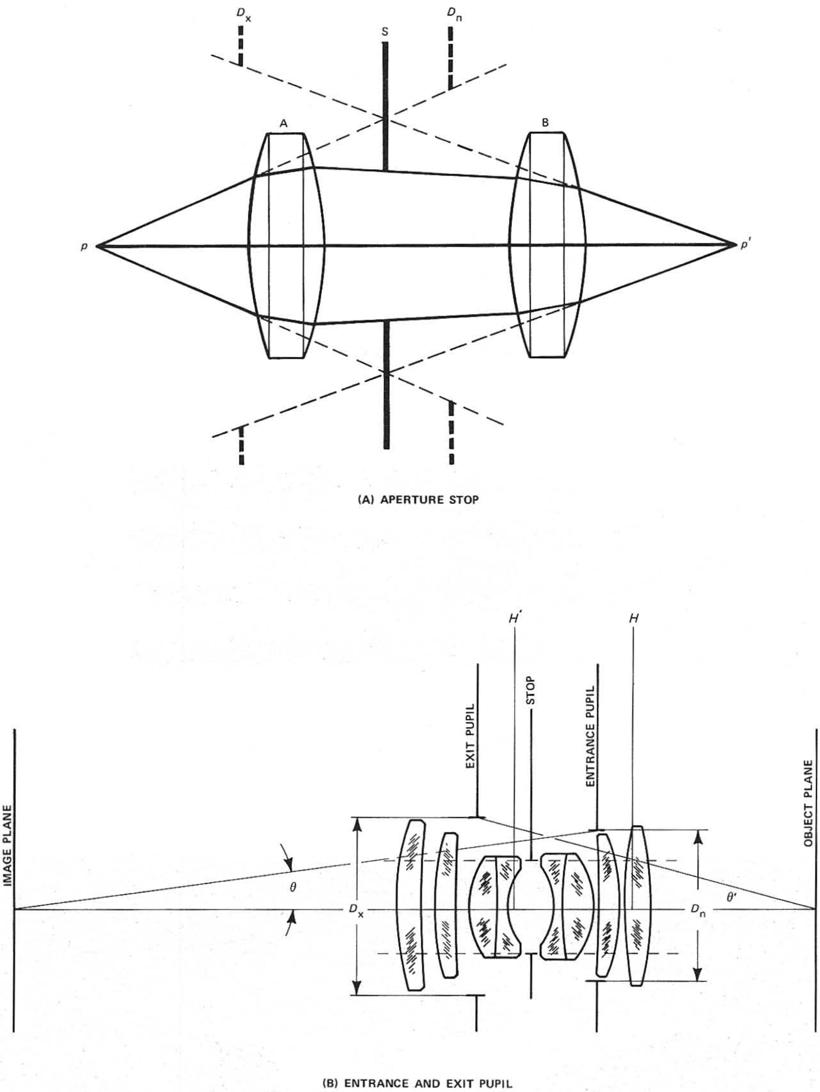
*Ref: 26. Monk, Ch 4
34. Southall, Ch 12
18. Jenkins and White, Ch 7
14. Hardy and Perrin, Ch 5



D_x
S
D_n
A
B
p
p'
(A) APERTURE STOP
H'
H
EXIT PUPIL
STOP
ENTRANCE PUPIL
IMAGE PLANE
OBJECT PLANE
θ
θ'
D_x
D_n
(B) ENTRANCE AND EXIT PUPIL

Fig. 4-27.

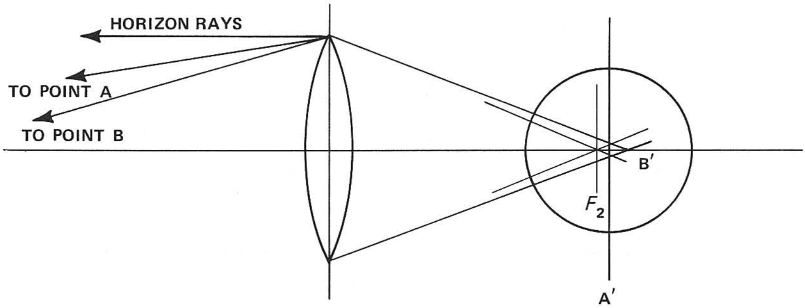


Fig. 4-28. Circle of confusion.

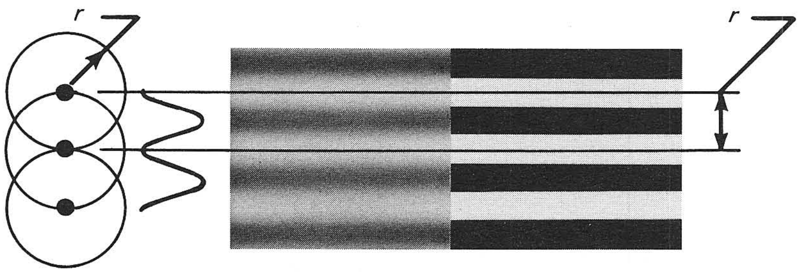


Fig. 4-29. Least circle of confusion.

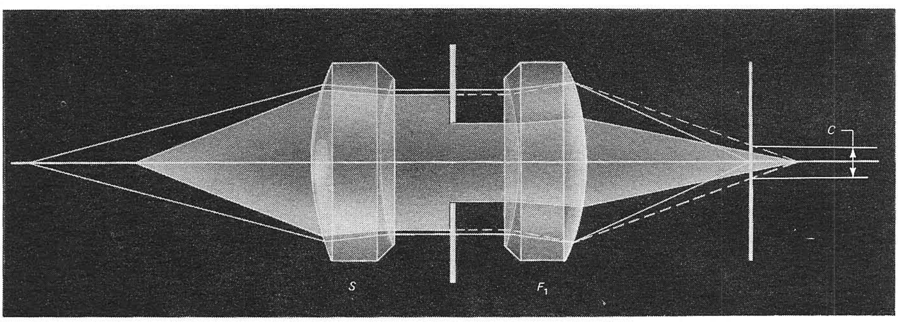


Fig. 4-30. Stop to reduce circles of confusion.

optimum focus

Those parts of a photograph that are out of focus are fuzzy because the images of points are circular areas rather than points; images of thin lines are broad lines. The criterion of optimum focus is least circle of confusion, Fig. 4-29.

resolution

If two adjacent points are imaged so that they can just be discriminated as two points, the distance between them will measure the least circle of confusion. Now if these points are moved during the exposure, so that they trace out lines, the distance between the brightest portions as well as the distance between the darkest portions will equal the radius of the circle. The number of line pairs of white and black lines define resolution in *lines per millimeter*, as noted in Chapter 3.

Fig. 4-30 shows the same situation as that in Fig. 4-28, but we have placed an aperture stop between the nodal points. This stop restricts the diameter of the cones of light that proceed to the image plane. As a result, the circles of confusion at F_1, the dimension c, are diminished effectively. The amount of light reaching the image plane is also diminished.

f-stops

f-numbers

The aperture stop is made adjustable, and calibrated in values of *f-stops* or *f-numbers* and expressed with a bar, for example: *f*/5.6, to indicate that the diameter of the aperture available for light transmission is the focal length of the lens, *f*, divided by the *f*-number. If a lens has a focal length of 50 mm, and the diameter of the entrance pupil defined by largest effective aperture is 25 mm, the *lens speed* will be *f*/2.

To simplify the terms, A will be used in equations using the *f*-number, rather than the accepted symbol, *f*/.

While the primary advantage of a controllable aperture is to increase depth of field, there are some important observations to note. On many occasions a fast film type will be overexposed because the exposure time cannot be made short enough, and it is necessary to stop down the lens. A more important note is that the improvement in overall focus and resolution does not continue as the aperture is made smaller but depends on the design of the lens. Modern fast lenses provide optimum resolution at an aperture several stops smaller than the largest opening. The particular point will depend on how the lens designer chose to adjust the various correction trade-offs.

close-up correction

The *f*-stops marked on the lens are calibrated for infinity focus. When you can arrange to focus on an object closer than 10 focal lengths, a multiplying factor should be applied to the marked aperture:

$$A_2 = \frac{\frac{u}{f}}{\frac{u}{f} - 1} A_1,$$

where u is the object distance. It is easier to calculate in units of focal length; $S = \frac{u}{f}$ focal lengths, then:

$$A_2 = \frac{S}{S - 1} A_1$$

At 5 focal lengths from the lens, a 50-mm, *f*/2 lens will have an aperture:

$$A_2 = \frac{5}{4} \cdot 2 = f/2.5$$

If the magnification is known, we can use

$$A_2 = A_1 \ (M + 1) \qquad \text{(Eq. 4-13)}$$

In the example above, $M = 1/4$, and $A_2 = 2(1.25) = f/2.5$.

Remember the form – *f*/16; *f* is lens focal length, and dividing it by the *f*-number results (approximately) in the diameter of the hole. An 80-mm lens at *f*/16 provides an entrance pupil (seen by the film) of 80/16 = 5 mm diameter. Remember also that the flow of light depends on the *area* of the aperture, and the area varies as the square of the diameter. Numbered *f*-stops (sometimes excepting the first) increase or decrease by the square root of 2. For example, beginning at *f*/2, the numbered stops are *f*/2.8, *f*/4, *f*/5.6, *f*/8 and so on, each stop calculated by multiplying the previous one by $\sqrt{2}$. Each time I increase the *f*-number by one stop, I cut the area of the aperture in half. Each time I increase the opening by one stop, I double the light flow. See Fig. 4-31.

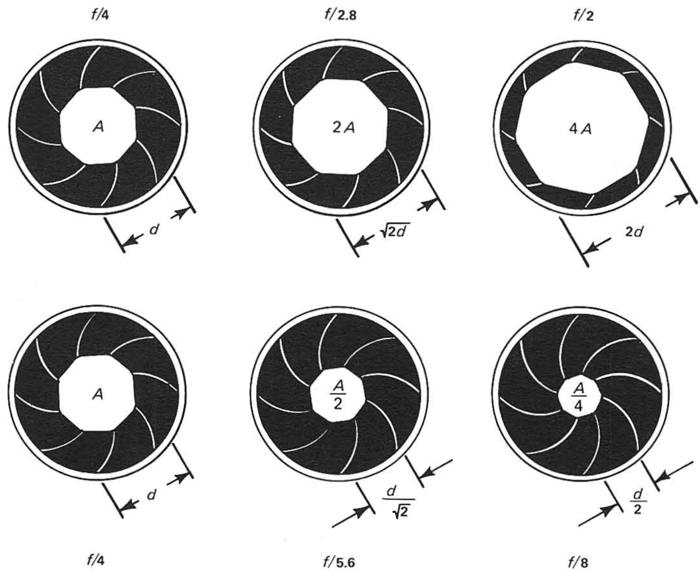


Fig. 4-31. Area of aperture increases inversely as the *f*-number.

4.10. DEPTH OF FOCUS, FIELD*

depth of focus

Depth of focus defines how precisely the image plane must be adjusted to the point of focus, when the diameter of the allowable circle of confusion is specified. The geometry of the problem is shown in Fig. 4-32; the diameter c of the circle of confusion increases directly as d, the distance the point departs from p', the point of optimum focus. The figure has been drawn for an on-axis point to simplify discussion, but the development is valid also for points off the axis.

acceptable circle of confusion

Several criteria have been established for acceptable circle of confusion, depending on the use of the photograph. The calculated resolving power of a young healthy human eye is about 1:3000, and a figure often used is 1:1000. For a contact print, or Polaroid print, viewed at ten inches, this implies an allowable circle of confusion of 0.01 inches, or 0.25 millimeters.

*Ref: 14. Hardy and Perrin, Ch 5
5. Cox, p 68

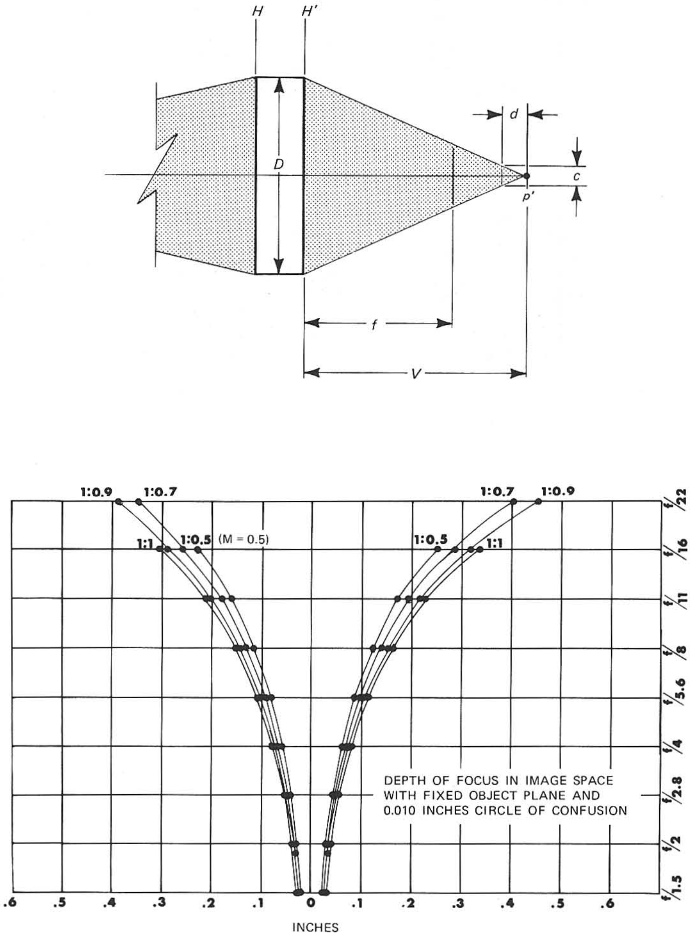


Fig. 4-32. Depth of focus.

In Fig. 4-33, D is diameter of entrance pupil, d is depth of focus, and c is diameter of circle of confusion. By geometrical proportion:

$$\frac{d}{c} = \frac{v}{D}, \text{ and by definition (Eq. 4-12),}$$

$$f\text{-number, } A = \frac{f}{D}, \text{ and } D = \frac{f}{A}, \text{ then}$$

$$d = \frac{cvA}{f}; \text{ and from Eq. 4-8 and 4-9}$$

$$v = f\,(M + 1), \text{ then}$$

$$d = \pm cA\,(M + 1) \qquad \text{(Eq. 4-14)}$$

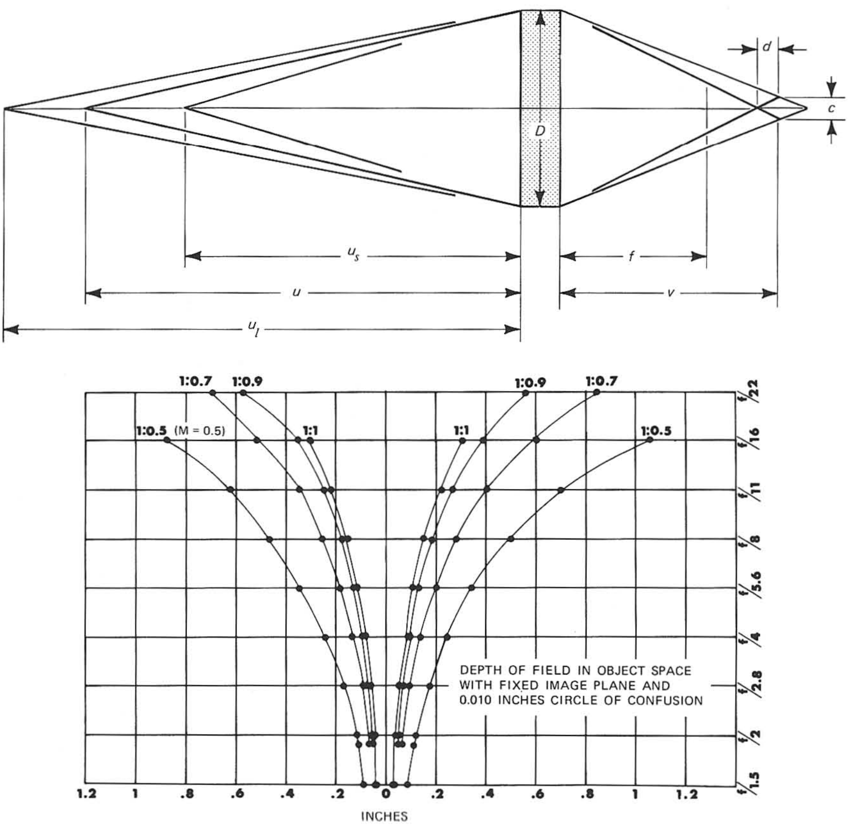


Fig. 4-33. Depth of field.

In most photographic situations, M is small, and effectively, $d = cA$. However, in oscilloscope cameras, M is usually significant.

depth of field

The conjugate side of the concept is termed *depth of field*, and is more useful to the working photographer. Depth of field defines the maximum axial distance between two object planes within which all points will be imaged with the acceptable circle of confusion.

When depth of focus has already been established by acceptable circle of confusion, magnification (not significant when $M < 0.1$) and aperture, the depth of field can be established for an *f*-number.

From Fig. 4-33, if u is the object distance, the depth of field will be $u_l - u_s$.

From Eq. 4-8, $u = \frac{fv}{v - f}$, and

$$u_s = \frac{f(v + d)}{v + d - f}, \text{ but} \qquad \text{(Eq. 4-15)}$$

$$d = cA(M + 1)$$

$$u_s = \frac{fv + fcA(M + 1)}{v + cA(M + 1) - f}, \text{ and} \qquad \text{(Eq. 4-15A)}$$

$$u_l = \frac{f(v - d)}{v - d - f} \qquad \text{(Eq. 4-16)}$$

$$u_l = \frac{fv - fcA(M + 1)}{v - cA(M + 1) - f} \qquad \text{Eq. 4-16A)}$$

Following is a typical calculation for a scope-camera lens:

$$f = 80 \text{ mm}; \; A = f/1.3; \; M = 0.5;$$

and using $c = 0.25$ mm for circle of confusion:

From Eq. 4-8 and 9:

$$v = f(1 + M) = 80 \cdot 1.5 = 120 \text{ mm}$$

$$u = f(1 + \frac{1}{M}) = 80 \cdot 3 = 240 \text{ mm}$$

From Eq. 4-15A:

$$u_s = \frac{80(120 + 0.25 \cdot 1.3 \cdot 1.5)}{120 + 0.25 \cdot 1.3 \cdot 1.5 - 80} = 238.07$$

$$\Delta u_s = 240.00 - 238.07 = 1.93 \text{ mm}$$

From Eq. 4-16A:

$$u_l = \frac{80(120 - 0.25 \cdot 1.3 \cdot 1.5)}{120 - 0.25 \cdot 1.3 \cdot 1.5 - 80} = 241.96 \text{ mm}$$

$$\Delta u_l = 241.96 - 240 = 1.96 \text{ mm}$$

Because 5 significant figures must be retained in the calculations, an ordinary slide rule is not adequate.

This particular solution defines allowable shift in distance between lens and phosphor plane. If the *f*-number were changed to *f*/4, the shifts would be plus 6.24 mm and minus 5.78 mm.

When the object distance is fixed, the film surface must remain within d distance of the true image plane:

From Eq. 4-14:

$$d = \pm 0.25 \times 1.3 \times 1.5 = \pm 0.49 \text{ mm}$$

4.11. LOSSES AND ABERRATIONS*

Most of our discussions have been based on a convenient assumption that most of the light is *paraxial*, that is, the rays do not make a large angle with the optical axis. Obviously, this condition is not true for wide-angle lenses, or for close conjugates where M approaches unity. These conditions exist in oscilloscope cameras and even in high-quality lenses cause light loss at the outer

$\cos^4$ law

limits of the image area. Fig. 4-34 shows an approximate idea of why this occurs. A detailed explanation of the *$\cos^4$ law* is given in Jacobs, *Fundamentals of Optical Engineering.*

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*Ref: 26. Monk, Ch 6
14. Hardy and Perrin, Ch 6
34. Southall, Ch 14, 15
5. Cox, p 98
17. Jacobs, Ch 4
18. Jenkins and White, Ch 9

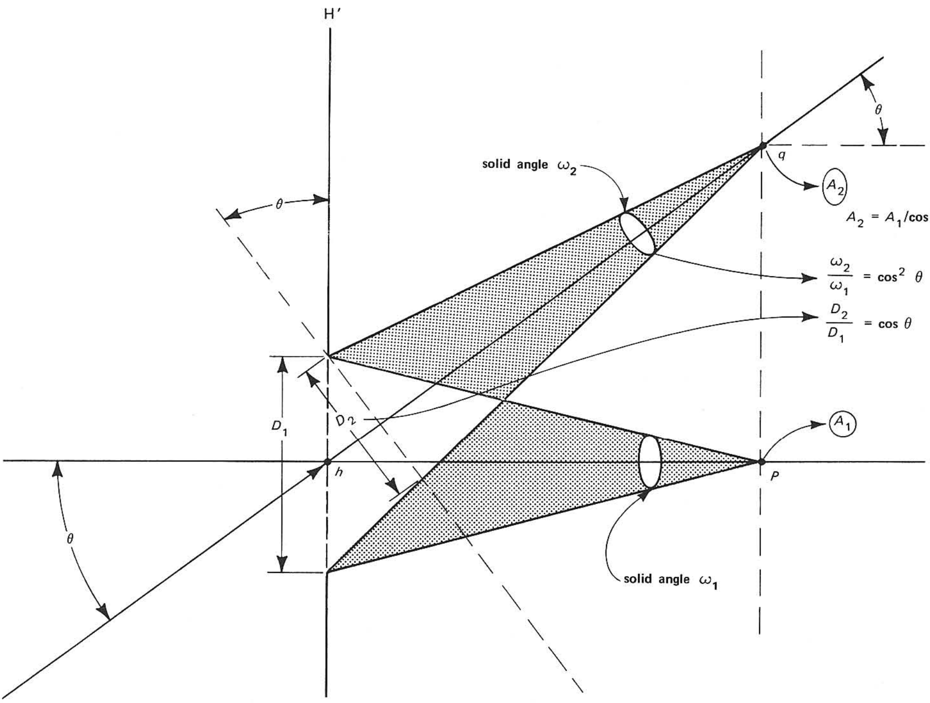


Fig. 4-34. Cos⁴ θ light falloff.

Even without considering vignetting, the area available for passage of light through the lens (Fig. 4-34) has been reduced by D_2/D_1, or cosine θ. Also, the cone (solid angle) subtended by the equivalent aperture D_2 is smaller than a cone with its apex at p by the ratio squared of hp to hq, or $\cos^2 \theta$. In addition, light strikes the image plane at q obliquely, diminishing the light by $\cos \theta$. The product of all these factors is $\cos^4 \theta$.

1. The area of the aperture represented by D_1 is reduced to $D_2 = D_1 \cos \theta$.

2. The solid angle ω_1 is reduced to $\omega_2 = \omega_1 \cos^2 \theta$.

3. The illuminated area of the image plane A_1 has been increased to $A_2 = A_1/\cos \theta$.

A convenient expression for this transmission loss is given in Cox, *Photographic Optics*, p 211:

$$K_c = \frac{f^4}{(f^2 + x^2)}, \qquad \text{(Eq. 4-17)}$$

where x is the distance of the image point from the axis.

A 80-mm lens recording a point 50 mm from the center of the photograph would show a loss of more than 50% compared to the illumination at the center. This loss is evident in any lens. Reflection and vignetting losses must be applied in addition.

vignetting

If you look through a lens system, open to its widest aperture, you will see the *vignetting* effect as you turn the lens to make a large angle with the line of sight. This vignetting is common to all lenses and results from the mechanical features of the lens assembly as well as from design tradeoffs or compromises, when stops are deliberately placed to limit off-axis rays. Fig. 4-35 shows the patterns of vignetting, indicating the extent of light losses to off-axis rays. A very fast multi-element lens may lose more from vignetting than a less expensive lens.

$\sin \theta$ expansion

Most of our discussion has been based on the behavior of paraxial rays, and conclusions were based on *first-order* optics. The terms *first order*, *third order*, etc., indicate the terms from the expansion of *sin x* used in the calculations. The value of sin x can be computed as precisely as needed from the expansion by extending terms:

$$\sin x = x - \frac{x^3}{3!} + \frac{x^5}{5!} - \frac{x^7}{7!} + \cdots$$

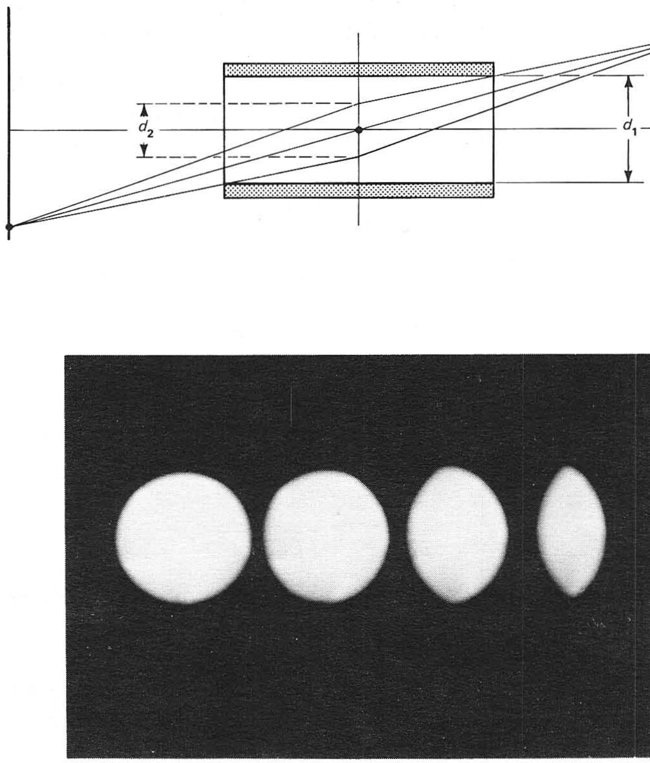
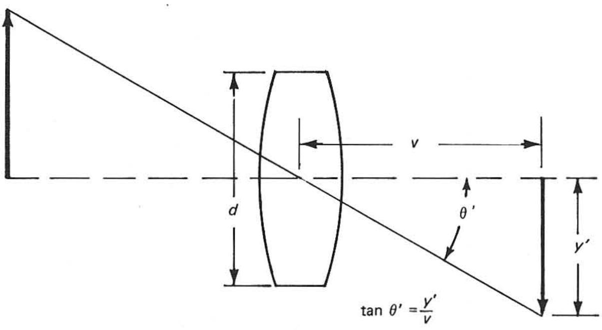


Fig. 4-35. Vignetting.

For angles less than 10° (0.18 radians), sin x is within one percent of the value of angle x in radians (180° = π radians), so only the first term is used of the expansion, x. For larger angles, x continues to grow larger than sin x and the next term $\frac{x^3}{3!}$ must be subtracted. This term provides the name *third order.* Some calculations require fifth-order terms. It is evident there are no second-order optics, and also how far we can go with first-order optics.



ABERRATION	VARIES WITH	INFLUENCED BY	EVIDENCE
Spherical	d^2	shape, aperture	unsharp focus at axis
Coma	y', d^2	shape, aperture	comet-shaped images of off-axis points
Astigmatism	y'^2	shape	shape of off-axis points change from 1 to – with change of focus
Field curvature	y'^2	glass, power distribution, stop position	corners and center focus in different planes
Distortion	y'^3	shape, stop position	barrel or pincushion effect at edges
Chromatic, lateral	y'	choice of dispersive powers	image surrounded by color fringe
Chromatic, longitudinal	—	choice of dispersive powers	red and blue focus in different planes

Fig. 4-36. Lens aberrations.

aberrations

For serious photography, corrections must be made for *aberrations*, the general optical term for what electronics people refer to as *distortion*. In optical terms distortion is one of several aberrations, and is not analogous to electronic distortion.

The chart in Fig. 4-36 lists the six categories of aberrations which must be corrected in a lens system. Each aberration in the list is appreciably affected by the one preceding it, and a correction made to one aberration influences the other. There are no closed-end formulas for lens designers, only an intricate set of feedback loops.

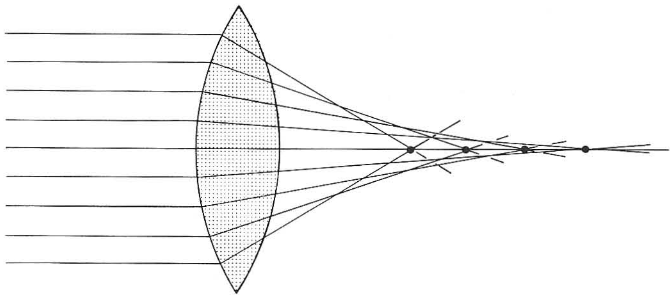


Fig. 4-37. Spherical aberration exaggerated.

spherical

Spherical aberration is exaggerated in Fig. 4-37. The rays farthest from the axis converge closer to the lens than the axis rays. The *di*vergent lens behaves the same, but the result is opposite to that with the *con*vergent lens. The two elements, with appropriate curvatures, can be cemented together to form a *doublet* with corrected spherical aberration, Fig. 4-38. Corrections are also made by altering the lens shape.

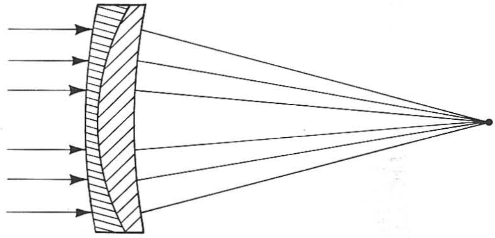


Fig. 4-38. Correction of spherical aberration.

coma

Coma appears as comet-shaped images of points *off the axis* oriented toward or away from the axis. It appears because concentric areas of the lens do not bend the light proportionally; the magnification for outer areas is greater than (or less than) that of the central areas. Coma arises primarily from *skew rays*, rays not in the same plane as the axis. For this reason, it cannot be illustrated adequately in two dimensions, but Fig. 4-39 represents a projection of the ray pattern. The properly-focused point of the object is at *A*. The circles result from skew rays through concentric areas that bend the light either more or less than required. The coma pattern is always aligned on a radial line from the optical center of the picture or image. The bright tail may be toward or away from the axis. Because an aperture stop limits the area of the lens being used, coma can be reduced by using smaller apertures. Coma is not evident at small field angles. In design, coma is corrected by altering the shapes of the lens elements, as indicated in Fig. 4-16.

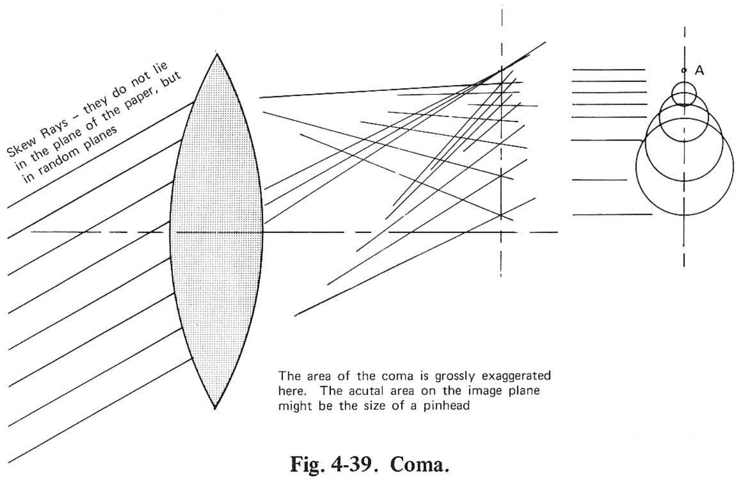


Fig. 4-39. Coma.

astigmatism

Fig. 4-40 illustrates how *astigmatism* affects the image. Horizontal lines appear to focus on one image plane and vertical lines on another. Between these two planes will be a plane which will image the point as a circle of least confusion. Those familiar with oscilloscopes adjust voltages on the electron gun to present a round spot; unadjusted astigmatism displays an elliptical spot. (See *Cathode-Ray Tubes* in this Circuit Concept series.) The CRT analogy does not hold completely; the optical astigmatism is orthogonal about the optical axis. The image of a spoked wheel, Fig. 4-41, is usually given as an example. Particular attention is given to correction of astigmatism in a good lens. Correction is done concurrently with correction of field curvature, as discussed below.

field curvature

If astigmatism is corrected at this point in the story, the image plane turns out to be a spherical surface, rather than a plane: Very inconvenient for loading film. This condition, a spherical image-surface, is the fourth aberration, *field curvature*, which is considered simultaneously with astigmatism, because the corrections are made concurrently. Field curvature and astigmatism are taken care of in a cheap camera by using a stop with a small aperture in front of a meniscus lens. In a lens system, correction is done by the separation of positive and negative pairs of lenses.

distortion

pincushion or barrel

Distortion, the fifth category of nonchromatic aberrations, results in straight lines of the object being imaged as curved lines. We sometimes see this distortion on CRT's; it shows the effect of a variation of deflection sensitivity because of a distorted magnetic or electrostatic field; we use the illustrative optical terms *pincushion* and *barrel* distortion. Optical distortion can be well corrected in photographic objectives by using symmetrical configurations or by proper placement of an aperture stop. Because the corrections for distortion imply sacrifices in other categories,

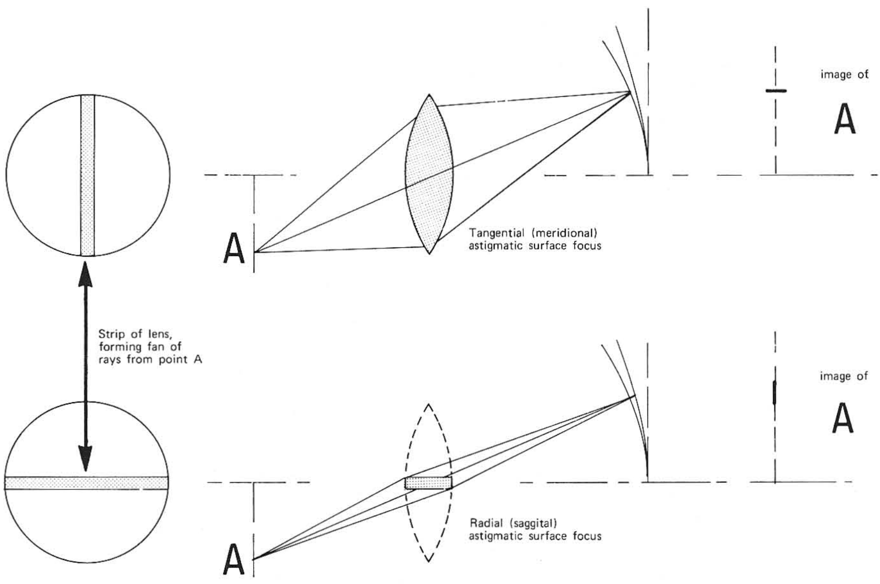


Fig. 4-40. Effects of astigmatism depend on position of the image plane.

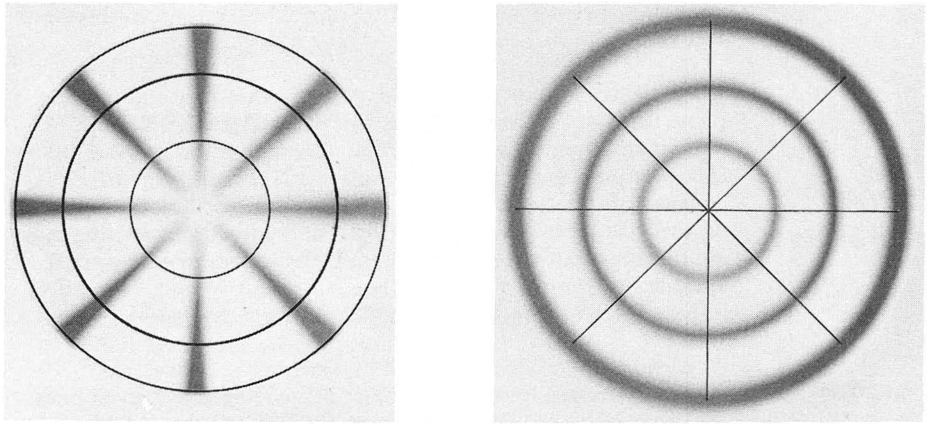


Fig. 4-41. Astigmatism causes spokes to be unfocused in the image plane where rim is in focus, and vice versa.

some well-designed lenses provide good correction only at particular conjugates. In any case, before you complain about a CRT with pincushion or barrel distortion, be sure your photograph displays the graticule lines.

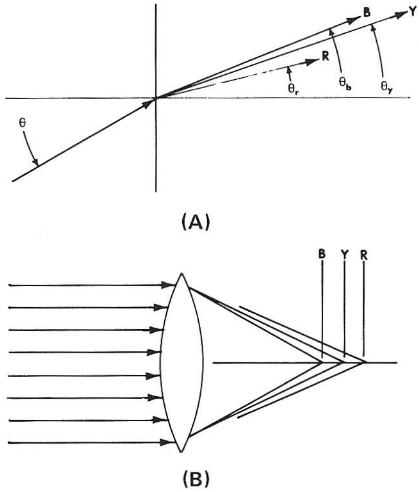


Fig. 4-42. Dispersion, exaggerated.

The sixth category is *chromatic aberration*. Fig. 4-42A shows a ray entering a transparent surface at an angle θ, with an angle of refraction θ_D. Also, $n_0 \sin\theta = n_1 \sin\theta_D$, where n_0 is the index of refraction on the entering side and n_1 is the index on the entered side. But n_1, for a particular material, is valid only for yellow light. The index for this material will be slightly different for other wavelengths of light. We have shown the positions of the red and the blue ray relative to the yellow, but the differences in angle are much smaller than the drawing shows. For a particular glass, at an angle of incidence of 30°, there will be a difference as much as 20 minutes of arc between the refracted angle of 400-nm light and that of 700-nm light. This variation of index with wavelength is referred to as *dispersion*. Different materials have different dispersive powers as well as indices of refraction. Fig. 4-42B exaggerates differences in focal points for axial chromatic aberration.

dispersion

Reference wavelengths for dispersion measurement are:

D (yellow) at 589 nm, the wavelength at which refractive indices are measured for the nominal value.

F (blue) at 486 nm, and

C (red) at 656 nm.

GLASS TYPE	n_C	V
Hard Crown	1.5190	60.42
Medium Barium Crown	1.5694	55.77
Dense Barium Crown	1.6570	50.81
Light Flint	1.5761	43.35
Double Dense Flint	1.8012	25.50
Special Barium Flint	1.7440	45.78

Fig. 4-43. Abbe number, *V*.

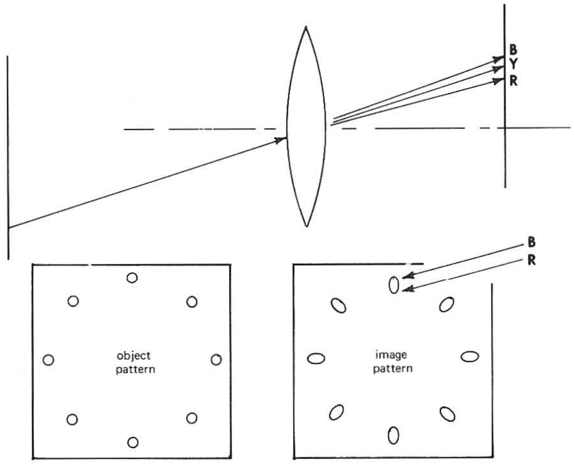


Fig. 4-44. Lateral chromatic aberration.

Other wavelengths of readily identified spectral lines are also used.

$$\text{Dispersive power } \frac{1}{v} = \frac{n_F - n_C}{n_D - 1} \qquad \text{(Eq. 4-18)}$$

Usually, the inverted form is used, (the Abbe number) V. Fig. 4-43 is a chart that compares refractive indices and inverse dispersion numbers of several types of glass. There is a myriad of glass formulas for the designer and his computer to draw from. The designer can select glasses for positive and negative elements with different indices, but the same dispersion. This *doublet* corrects the chromatism.

Lateral chromatic aberration is expressed by Fig. 4-44. This aberration is seldom of serious consequence in black and white, but with color film may result in a color-fringing effect in the outer areas of the picture.

4.12. RESOLVING POWER*

lines per millimeter

Resolution is one of the criteria for evaluating the photographic system, expressed in lines per millimeter (line pairs). A resolution chart established for testing resolving power of a lens is shown in Fig. 4-45.

Lens resolving power cannot be measured properly by measuring elements of an image on ground glass, because the grain of the glass may be larger than the resolution to be measured. The obvious method is to take photographs and measure directly from the film, keeping the image plane parallel to the object plane within precise limits, and the optical axis precisely normal. Measurements made in this way will also include any limitations of film resolution. Also, the resolution recorded will depend on the contrast of the object.

modulation transfer function

Many of the observations on resolution and acuity discussed in Chapter 3 also apply to optical devices; the modulation transfer factor, MTF, discussed in Chapter 3, is used as a figure of merit for lenses as well as for film and can be applied to a system, if certain limitations are observed.

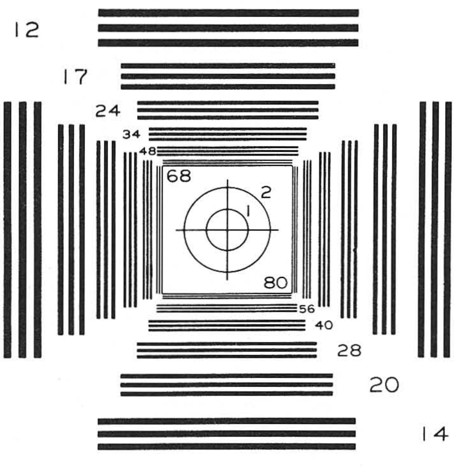


Fig. 4-45. NBS long-line resolution chart.

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*Ref: 26. Monk, Ch 12
14. Hardy and Perrin, Ch 7
17. Jacobs, Ch 8
5. Cox, p 215
18. Jenkins and White, Ch 14

reflection losses

flare

Multiple reflections of bright objects toward which the camera is directed can be observed by looking directly into the lens; all the light so reflected is lost. The losses increase exponentially by the total surfaces in the lens. Many camera lenses have as many as ten air-to-glass surfaces. If the loss at each surface is 4%, a reasonable figure for an uncoated surface, the transmission through each surface will be 0.96 and the total transmission will be $(0.96)^{10} = 0.66$. You can perhaps afford this loss with a fast lens and fast film, but much of the light coming into the camera has to bang around lens surfaces until it gets lost, either in the surface of the lens barrel or in the surface of the film where it appears as fog.

$$\text{Transmission, } T = (1 - \sigma)^N \text{, where} \qquad \text{(Eq. 4-18)}$$

σ = loss per surface

N = number of air-to-glass surfaces

lens coating

The solution to this light loss and noise is to apply a transparent coating to the glass of a thickness that acts as a quarter-wave trap, and reduces the reflected light to less than one percent. Practically all lens assemblies now use coated elements. For work with light at a particular part of the spectrum, as provided by P11 or P31 phosphors, the thickness of the coating may be adjusted to save another fraction of a percent in reflection.

4.13. POWER TRANSFER*

Useful light-power efficiency depends to some extent on the lens corrections. If the resolving power is poor, more energy will be needed to record the trace. The importance of the individual corrections will depend on the characteristics of the system outside the lens, as well as on the measurement requirements. The light-power losses, or their complements, the transmission factors (efficiency factors) must be included in the exposure equation.

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*Ref: 17. Jacobs, Ch 4

The individual efficiency factors can be multiplied together, resulting in an overall factor, K, accounting for the total on-axis loss. The power-transfer equation will provide the illuminance on the film:

$$E_e = \frac{\pi BK}{4\,A^2\,(M + 1)^2} \qquad \text{(Eq. 4-19)}$$

where: B = flux per unit area of uniformly diffusing surface normal to the axis.

K = transmission of the lens for small angles (not including $\cos^4$ law, or vignetting).

A = relative aperture: f-number indicated on lens.

M = magnification: image-to-object ratio.

The same expression can be used in terms of watts instead of lumens if B and K are adjusted accordingly.

Contrast factors arising from incompletely corrected aberrations will not affect the system seriously. Resolving power will be significant in systems using beam diameters on the order of one mil (.025 mm). For most oscilloscope recording, lens resolution will not be of much consequence. The most obvious lens aberration; one often noticed is distortion. Where no graticule lines are recorded and no traces are straight lines, barrel and pincushion distortion may not be apparent, but graticule lines accentuate the aberration. Other than optical distortion, the only other contribution of the lens to inaccuracy would be in the magnification setting. If magnification is a critical factor, it can be measured and the ratio marked on the barrel for the particular front conjugate used.

Fortunately, hardly anything can be done to improve a correctly-assembled lens. When the temptation arises to take a lens apart to see how it works or to improve it, choose one that will never be used again. A very slight decentering or axial deflection will upset the correction compromises.

Protect the glass surfaces from shock, high-energy radiation, chemical fumes, and from fingers, which deposit acids that eventually affect the coating and the glass.

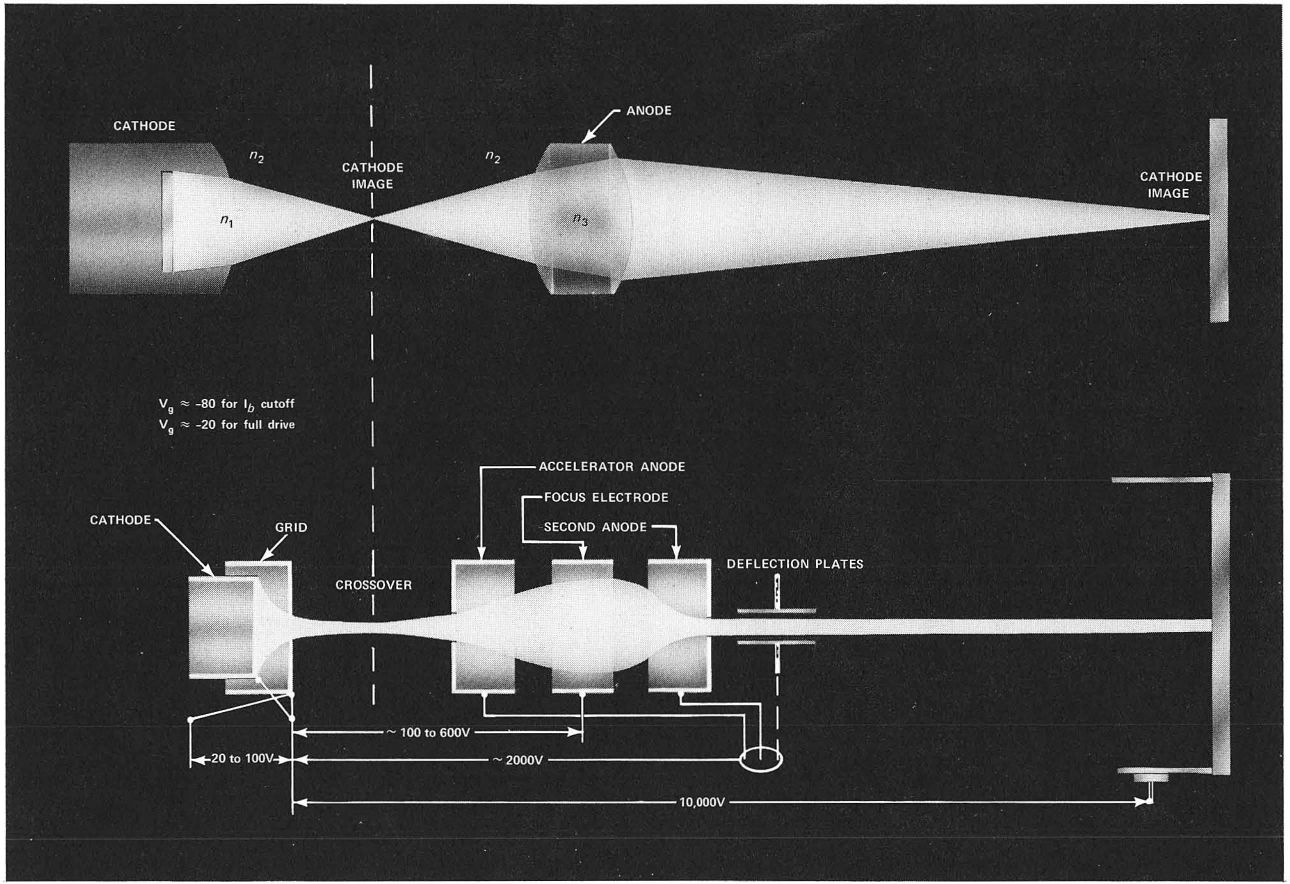

Fig. 5-1. Electron lens and CRT schematic.

5

CATHODE-RAY TUBES

The following discussions, except where noted, pertain to electrostatically focused and deflected CRT's, because that type is most commonly used for oscilloscopes.

5.1. FORMING THE BEAM*

source

The source of electrons for the CRT beam is a hot oxide-coated cathode; the power for the beam is supplied by the final anode. The energy of the individual electrons in the beam is delivered to crystals in the phosphor, releasing energy as photons. The energy radiated per square centimeter of phosphor surface is directly related to the electron density of the beam.

beam shape

Electrons are driven off a plane surface of the cathode, normal to the tube axis, as shown schematically in Fig. 5-1. The grid is a metal cup, having a small hole as an aperture and aligned in front of the cathode. An adjustable negative potential is applied to the grid with respect to the cathode. The first anode is a cylinder with apertures for the beam; its potential is fixed at a point positive with respect to the cathode. These three elements provide an electrostatic field shaped in such a manner that electrons emitted from the cathode are constrained in a beam. The diameter of an unconstrained beam would increase rapidly because of mutual repulsion of electrons; the field established by the relative potentials on the first three elements brings the beam to a minimum dimension at a point between grid and anode, the *first crossover point*. This minimum dimension limits the minimum size of the spot focused on the phosphor.

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*Ref: 30. Radiation Lab, Ch 2
38. Spangenberg, Ch 13, 15
40. Tektronix

beam flow

The flow of beam current is controlled by adjusting the potential on the grid with respect to the cathode. In many CRT's, beam current is cut off by driving the grid more negative (blanking) or conversely, beam current is turned on by driving the grid more positive (unblanking). Some CRT systems use *deflection blanking*; instead of being cut off, the beam is electrostatically deflected away from the anode aperture during retrace.

blanking

As the beam continues through the deflection system, its diameter is controlled by a second focusing field established by potentials on the focus ring, adjacent to the anode, and on the second anode, which provides another aperture. The potentials on these elements are controlled separately by the operator to focus the spot on the phosphor, and to correct astigmatism introduced by the deflection system (Fig. 5-2).

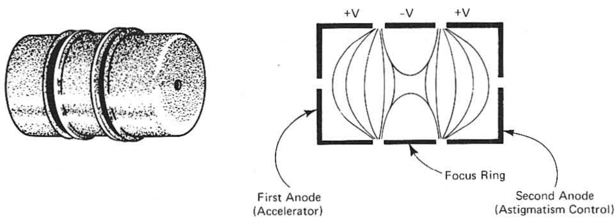

Fig. 5-2. CRT anode and electric field.

5.2. DEFLECTION ELECTRONICS*

electrostatic

The electrostatic deflection system provides two pairs of plates parallel to the beam axis; one pair each for horizontal and vertical deflection. The plates usually connect to a network providing electrical symmetry, a positioning function, and an adjustable potential to the reference level. Fig. 5-1 illustrates typical voltage relationships between CRT elements.

One of the significant specifications of a CRT is *deflection sensitivity*, the deflection on the faceplate per deflection volt, often expressed in cm/volt. *Deflection factor*, the inverse of deflection sensitivity is approximately:

$$\text{DF} = \frac{V_d}{Y} = \frac{2dV_a}{lL} \text{ volts per unit scan} \qquad \text{(Eq. 5-1)}$$

where V_a = accelerator anode voltage; $V_d = V_1 - V_2$; the other dimensions are indicated in Fig. 5-3.

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*Ref: 30. Radiation Lab, Ch 2
38. Spangenberg, Ch 15
40. Tektronix

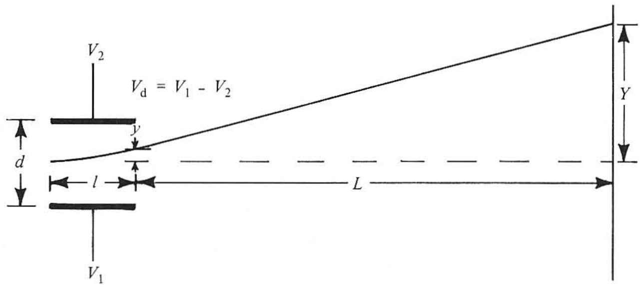

Fig. 5-3. Development, electrostatic deflection.

Some of the tradeoffs in CRT physical dimensions become evident when Equation 5-1 is expressed as deflection sensitivity:

$$\frac{Y}{V_d} = \text{DS} = \frac{lL}{2V_a d} \text{ usually in centimeters per volt} \qquad \text{(Eq. 5-2)}$$

The deflection sensitivity expressed is that for a monoaccelerator CRT (no acceleration after beam deflection). The factors do not quite vary linearly in a post-acceleration CRT.

risetime

design criteria

Risetime is a figure of merit for circuit response and defines the minimum time required for a DC off-to-on signal to be completed. See Fig. 1-3. It is usually defined as the time interval between 10% and 90% of the final value. The design tradeoffs can be compared by inspecting Fig. 5-3 and Eq. 5-1. The desired deflection Y, on the CRT face, is established by human engineering factors such as eye resolving power and distance, and ease of measurement as well as practical trace width. If the criterion of risetime is established, the relative effects of the other dimensions are deduced. Distance to screen, L, is limited by physical considerations of equipment, as well as by difficulty in maintaining a linear deflection and a small spot. Distance between deflection plates, d, will limit the aperture for the deflected beam, and will control the capacitance that must be driven by an amplifier. Length of deflection plate, l, can be increased at a cost of additional capacitance and precision structure problems. Anode potential (V_a) must be established at the point at least where the excited phosphor can be seen at the fastest trace to be displayed. After these constants have been established to a first approximation, an amplifier must be provided to drive the plates to V_d volts at the risetime and within the linearity specified. The energy demand for a particular excursion will vary approximately with the square of the deflection, and approximately inversely with the risetime. The demand for changes of energy in the CRT beam itself is not as severe; when modulation of the beam, *Z axis*, is required, the risetime is less critical than that of X or Y deflection. Most of the information is provided by the horizontal and vertical amplifiers.

The previous discussions, intended to establish energy relationships, do not include some of the practical approaches used. For example, Eq. 5-1 implies that deflection sensitivity varies inversely with the total acceleration voltage through which the beam drops. Some of this penalty for additional beam power is avoided by providing additional acceleration *after* deflection – post-deflection acceleration. Also, deflection plates are shaped to allow close spacing at the beginning of the deflection field and wider spacing at the end of the deflection field, so the plates do not intercept as much of the beam.

post-deflection acceleration

shaped plates

5.3. BEAM POWER DENSITY*

Measurements of distribution of beam power density have been made and can be calculated, but it is easier to measure the phosphor spot size and infer the beam power distribution (Fig. 5-4).

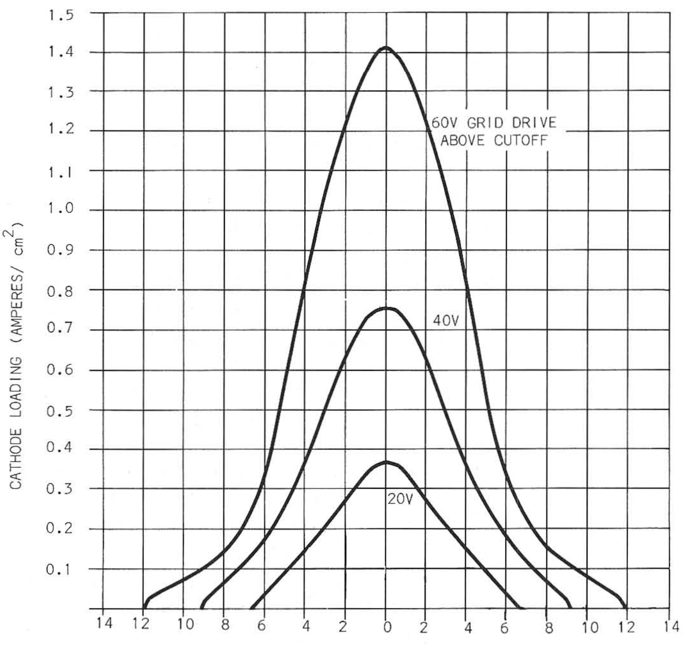

Fig. 5-4. Showing a high current density in the center of the cathode emitting area, falling off toward the edges. Current density changes with grid voltage.

*Ref: 30. Radiation Lab, Ch 2
38. Spangenberg, Ch 13

The beam cross section at the phosphor plane is an image of the beam at the first crossover point. The current (electrons) distribution of the beam at the phosphor depends on the triode parameters that influence current density at the crossover (Figs. 5-1 and 5-2). Beam-current density increases with accelerator voltages and usually increases with beam current at low beam currents, then, after a peak, decreases. Beam-current density characteristics of different CRT designs vary. Where resolution requirements outweigh writing rate, the designer may choose to run the tube at relatively low beam current, and use a higher accelerator voltage but a lower post-accelerator voltage.

5.4. POST DEFLECTION ACCELERATION*

Post-deflection acceleration (PDA) is provided by extending the electrostatic field out to the phosphor plane. Ideally, the post-deflection field would increase the beam velocity without changing beam direction. This implies an electrostatic field parallel to the CRT axis in the area of beam traverse. An effective way of providing this field is by applying a conductive helix to the inside of the envelope (Fig. 5-5A). When a high voltage is applied to the faceplate end of the helix, a uniform voltage gradient exists in the beam area, down as far as the deflection plates. This design provides additional beam power density without a corresponding loss in deflection sensitivity.

helix

An appreciable improvement in deflection sensitivity is realized by introducing a fine mesh immediately after the deflection plates at the potential of the first anode. The helix extends only part way toward the front of the tube; the rest of the area is a uniform conductive coating, as indicated in Fig. 5-5B. The mesh shields the deflection plates from the field of the helix, preventing convergence of the scan pattern; the result is greater deflection sensitivity. The tradeoffs are a loss in beam current to the mesh, and failure of the beam to converge to a finer spot at the faceplate. To offset the loss in beam power, the final anode voltage is increased to as much as 24 kV. While the minimum visible trace width is larger than that of the normal PDA CRT, and the beam current density usually less, the beam power density is greater. At the high beam currents needed for fast transients, the trace widths are comparable. Since the final anode voltage is higher and the beam power density is greater, faster photographic writing rate is effected.

mesh

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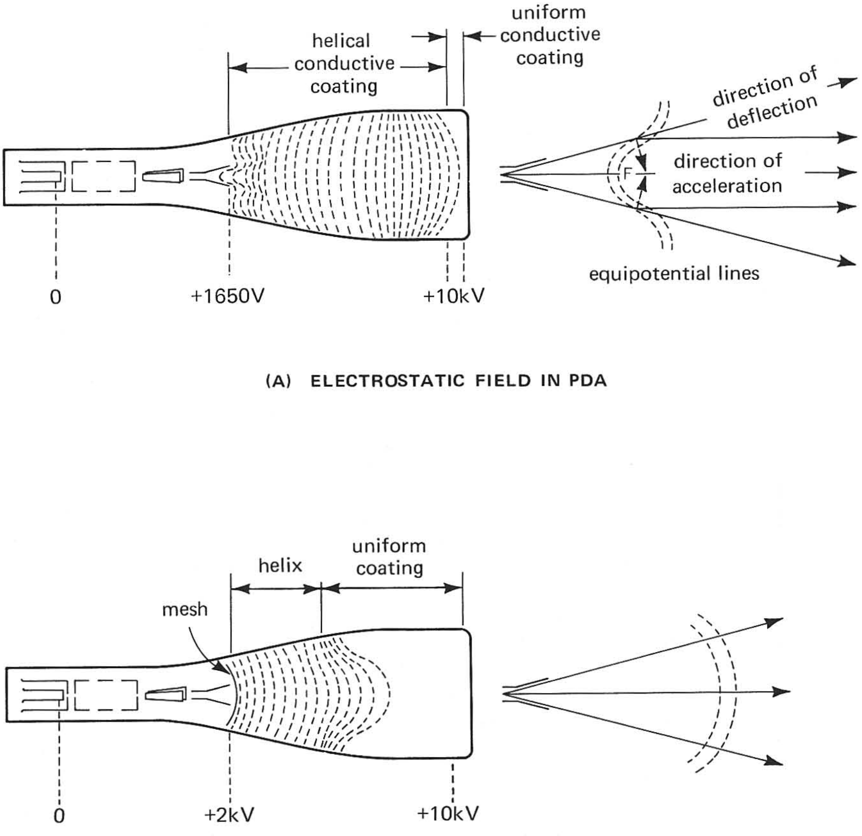
*Ref: Radiation Lab, Ch 2



(A) ELECTROSTATIC FIELD IN PDA

(B) FIELD IN PDA WITH MESH

Fig. 5-5.

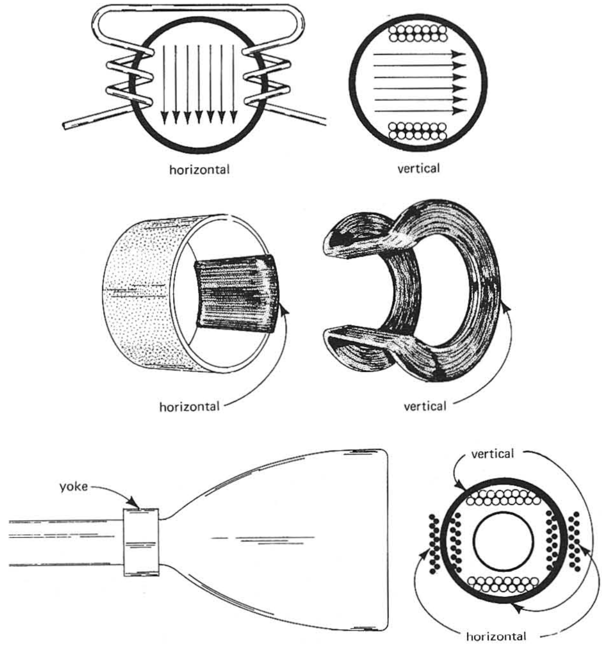


Fig. 5-6. Magnetic deflection arrangement.

5.5. MAGNETIC DEFLECTION*

When a large-area display must be provided without lengthening the CRT, magnetic deflection is used (as in TV tubes). Fig. 5-6 illustrates physical arrangements and the corresponding direction of forces.

An expression for magnetic deflection that illustrates the effects of the parameters is:

$$\sin\theta = \frac{0.30\ Hl}{V_a}$$

θ = deflection angle

H = flux density in gauss

l = axial length of deflecting field in cm

V_a = accelerating anode voltage

A complete development of magnetic deflection principles is found in Radiation Laboratory Series 22, Chapter 8.

*Ref: 30. Radiation Lab, Ch 2, 8

5.6. DISPLAY-SURFACE CHARACTERISTICS*

aluminum film

On CRT's operated with final-anode voltage greater than 3 kV, the first surface facing the electron beam is an aluminum film evaporated on the back of the phosphor (Fig. 5-7). This film acts as a conducting surface to drain off the excess electrons delivered by the beam and provided by secondary emission, preserving the polarity of the screen area and removing surface charges. A major advantage of the film is the reflection of light back through the faceplate. There is also a measure of insurance against burning the screen through carelessness. The small penalty for the advantage is a loss of energy in penetrating the aluminum film. On CRT's with less than 4 kV total anode voltage, only a very thin film is used.

phosphor deposition

Under the aluminum film is the phosphor. There are several methods of phosphor application, depending on the objectives. Thin, polished phosphor surfaces are less efficient for photographic response, for persistance characteristics, and in some cases for spectral response. Phosphors on most CRT's are applied by settling them in an aqueous suspension; this method usually provides the best energy transfer efficiency. Phosphor particle size and total thickness affect transfer efficiency and front-surface characteristics, such as resolution.

phosphor thickness

A balance of tradeoffs is necessary to optimize the thickness of the phosphors. A thin phosphor does most of its radiating close to the glass surface, where most of the radiation is effective, but there are fewer crystals in the electron path to be activated, so many electrons merely heat up the faceplate. A thick phosphor provides more activity, but some of it will be too far from the faceplate to be useful, and those electrons that do penetrate close to the glass surface have lost much of their energy.

burn

Even with the more efficient phosphors, 90% of beam energy is lost; most of it is dissipated by the faceplate as heat. Fig. 5-7. If the dense spot remains stationary so long that the faceplate receives energy at a higher rate than it can be dissipated, the high local temperature will destroy the phosphor at that point. Phosphor burn susceptibility depends primarily on the phosphor composition, particle-size distribution, and the nature of the phosphor-bonding to the glass.

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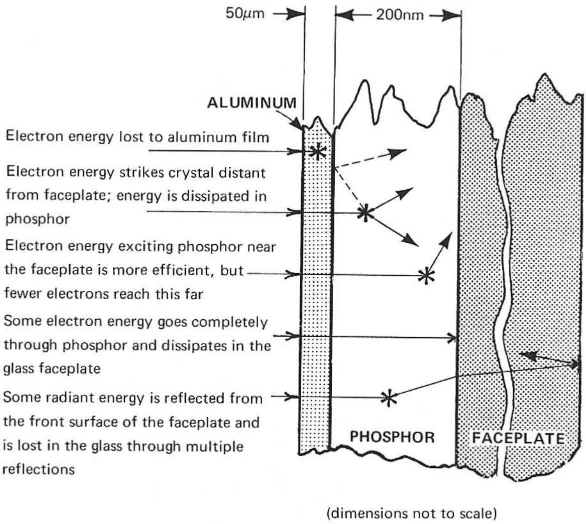
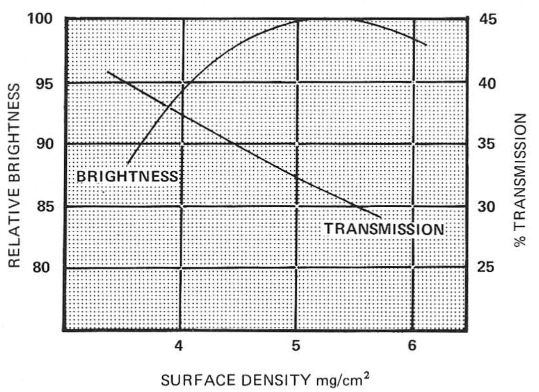
*Ref: 30. Radiation Lab, Ch 18
23. Leverentz
36. Sproull



(A) Mechanics of energy losses at phosphor plane.



(B) Relative brightness and transmission as a function of phosphor surface density.

Fig. 5-7.

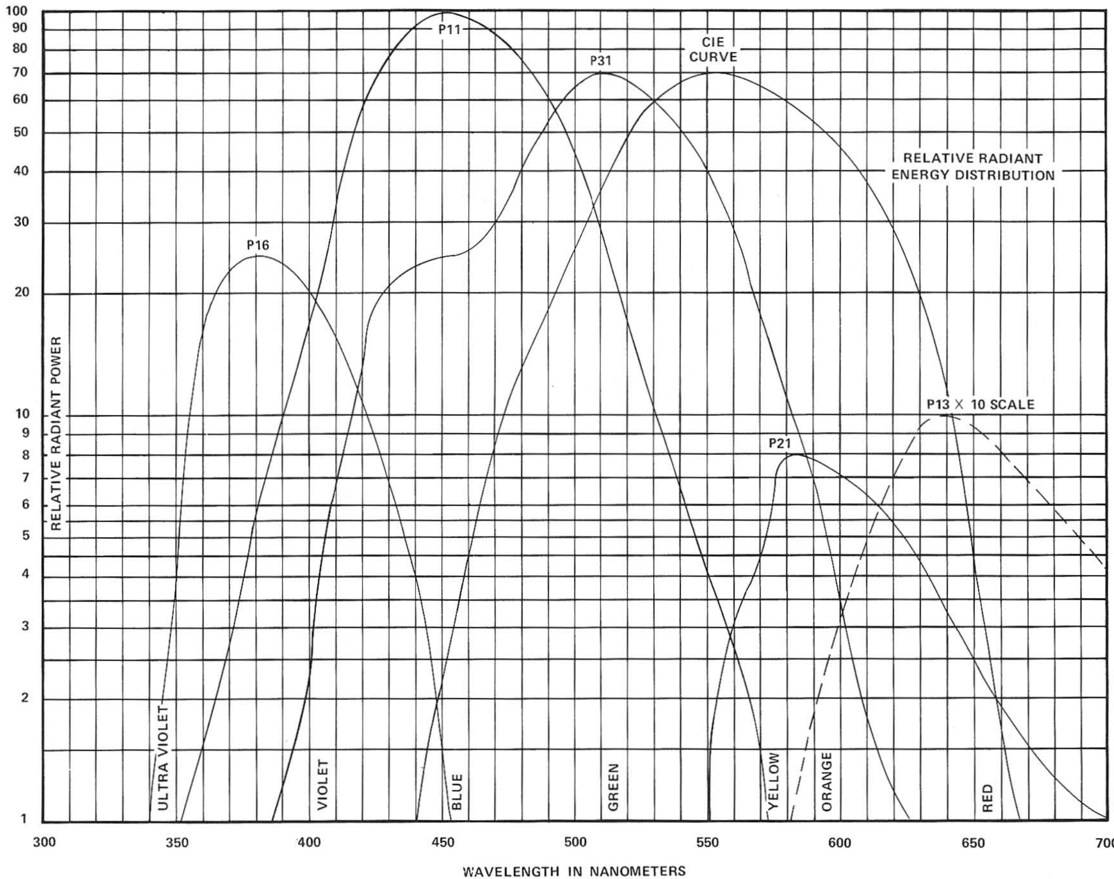


Fig. 5-8. Radiant energy distribution.

Resistance to burning of some common phosphors is listed below; P15 will stand perhaps 500 times the beam power at which P19 will burn:

Very low	P19
Low	P16
Medium low	P32
Medium	P1, P7, P11
Medium high	P2
High	P31
Very high	P15

phosphor energy distribution

Fig. 5-8 shows relative energy distribution of some useful phosphors. The CIE curve is included to show the *visible* portion of each phosphor's energy. Note that much of the radiant energy of P16 extends into the ultraviolet area where the transmission of most glasses falls off rapidly. The several curves represent radiation at relatively low beam-current densities – some double-layer phosphors show a shift of relative amplitude in parts of the spectrum with change of beam current.

photographic and visual effectiveness

Fig. 5-9 compares photographic effectiveness with brightness. The photographic effectiveness bars are referenced to P11 phosphor at 100; the visual effectiveness bars are referenced to P31. Note that longer-wavelength phosphors are much less powerful; also, their photographic effectiveness is much poorer than their visual effectiveness.

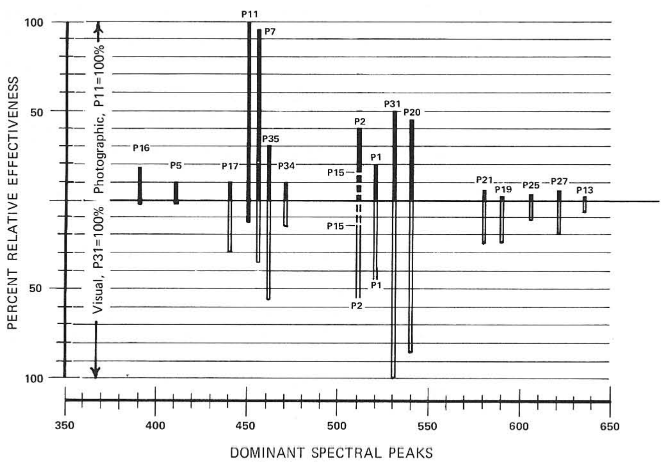


Fig. 5-9. Phosphor spectral characteristics.

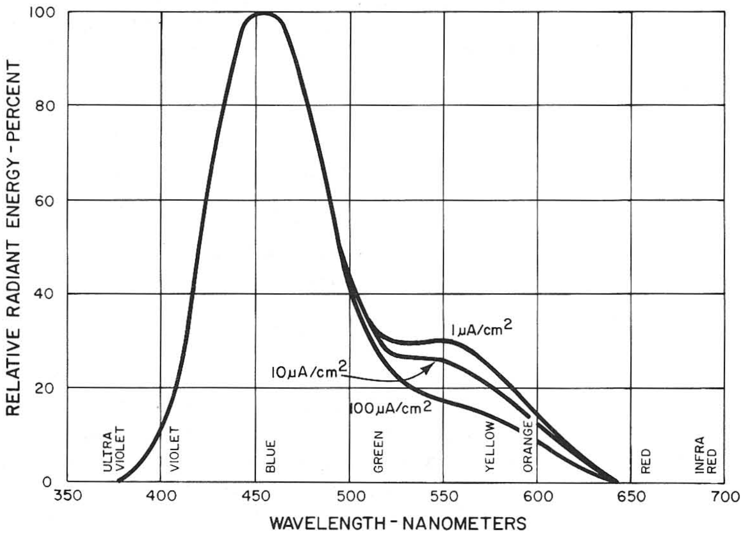


Fig. 5-10. Radiant energy distribution of phosphor P7.

two-layer phosphors

Some phosphors, such as P7 and P14, are made up of two separate layers. The layer nearest the faceplate has the desired display characteristics, and is excited by the first phosphor which radiates energy at a shorter wavelength. Fig. 5-10 shows the radiant energy distribution of P7. Under steady conditions, the first phosphor struck by the beam (P11) radiates most of the energy about a wavelength of 455 nanometers; the minor radiation from the second phosphor (P28), around 550 nm, is much less powerful. However, 10 milliseconds after the beam has been cut off, the longer wavelength radiation is still evident, while the P11 power has decayed to less than one percent. See Fig. 5-11.

fluorescence

phosphorescence

Fluorescence implies immediate radiation of energy received. Phosphorescence is radiation that continues after the excitation has been removed.

risetime

build-up time

Risetime of a phosphor is specified as the interval between initial excitation and 90% of steady-state brightness. Build-up time defines the increase in light output under a series of excitations, an exponential increase in luminescence with each additional pulse of excitation. These criteria are not always significant, and not always specified.

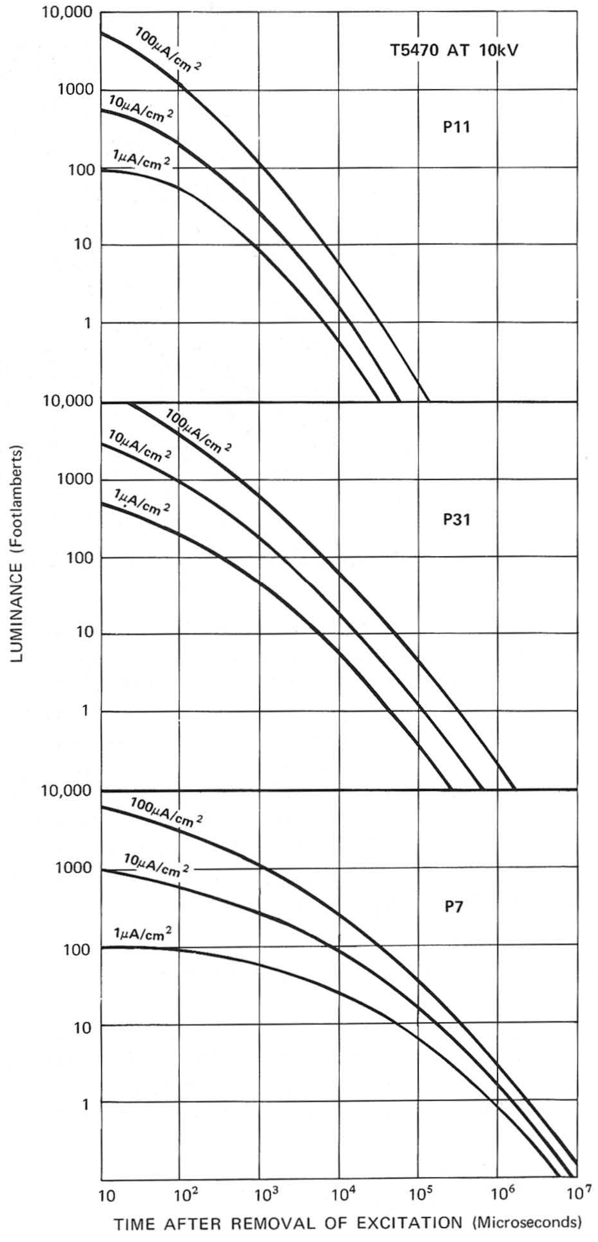


Fig. 5-11. Phosphor decay characteristics.

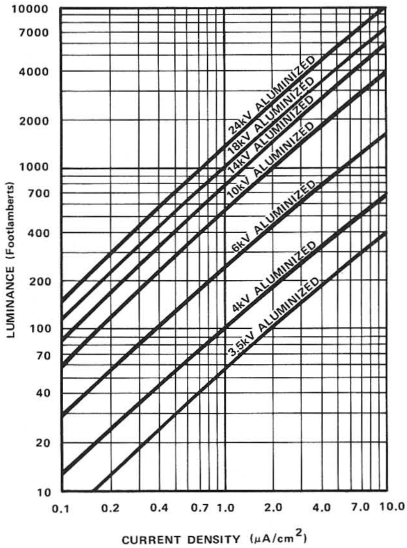


Fig. 5-12. Luminance as a function of current density, P31.

decay time

persistence

Decay time (persistence) is specified as the interval between removal of excitation and the decay to a specified fraction of original luminance, sometimes $1/e$, sometimes 10%. To provide consistent figures it is usually necessary to specify one or more of the following conditions: V_a, I_b, current density, number of scans, or time interval of initial excitation. The decay characteristics for a particular phosphor will sometimes be longer after low-power excitation than after high-power excitation. Fig. 5-11 compares decay characteristics of 3 different phosphors on the same time scale. Note that decay appears to be more rapid at higher beam-current densities.

5.7. MEASUREMENTS OF DISPLAY CHARACTERISTICS*

luminance

Fig. 5-12 illustrates how luminance varies with beam-current density and with final-anode voltage. The curves are not straight lines, as they appear to be, but usually indicate a decrease in phosphor efficiency as current density increases and the phosphor becomes saturated.

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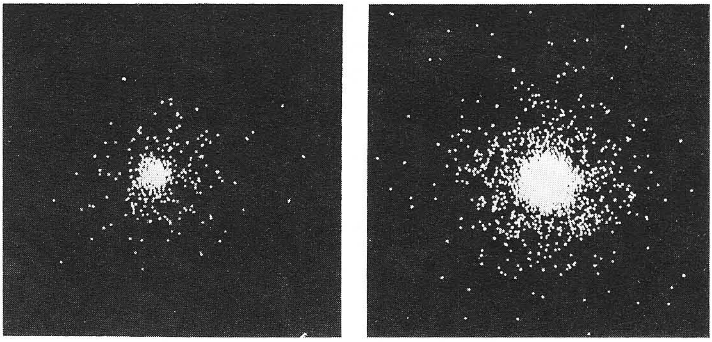
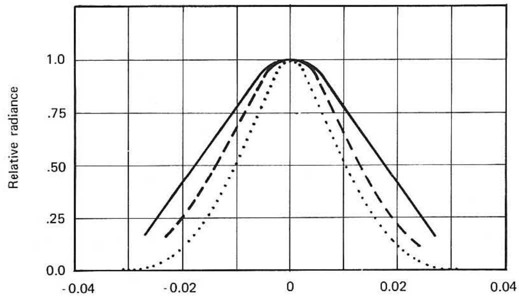
*Ref: 30. Radiation Lab, Ch 17
41. Tyler
6. Christiansen and Donaghue
7. Derr
37. Sawtelle
4. Bryden



(A) and (B) Representation of electron pattern as beam strikes the faceplate.



(C) Beam density profiles for three beam currents, inferred from measurements of radiance across the trace.

Fig. 5-13.

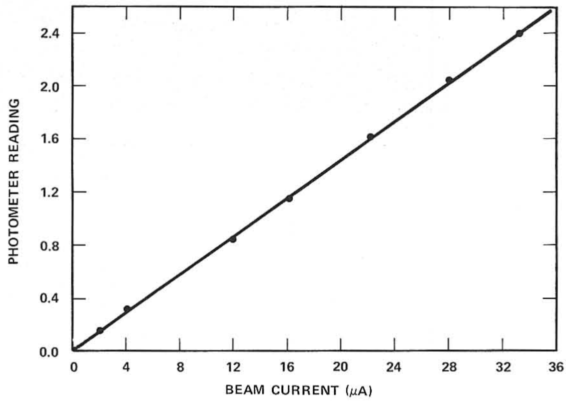
beam power distribution

The distribution of power in the beam is affected by cathode loading (cathode-current per unit area of cathode surface), electron optics governing the size of the cathode image at the crossover point, the electro-optical stops, and beam focus at the phosphor plane. Fig. 5-13A represents a cross section of electron distribution in the beam at low-beam current and B, at high-beam current. Measurements are inferred from beam-trace measurements on the phosphor; actual measurements would require more complex equipment and procedures, without providing more useful data. Fig. 5-13C is a family of curves taken at different beam currents, showing the differences in relative trace profile.

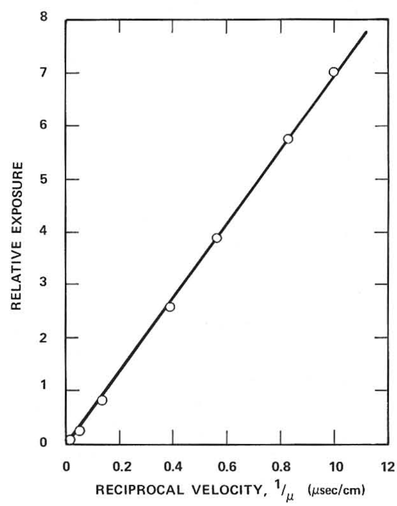
The dependent variable in these curves is radiant flux per unit area, that is, power per unit area. For the data to be valid, the anode voltage must remain constant. Because the data relate to a fast-moving spot in useful applications, they cannot validly be retrieved from a stationary spot.

On helical post-deflection CRT's, the total power density measured at the face of the CRT varies directly (within a few percent) as beam current until the phosphor is saturated; that is, until the phosphor cannot convert more power to light, dissipating the additional power in heat (Fig. 5-14A).

When beam current is held constant, energy density at the phosphor will vary directly with inverse sweep speed (time per division) as in Fig. 5-14B.



(A) Luminance increases directly with beam current.



(B) With beam current constant, energy per unit area increases inversely with spot velocity.

NOTE: Data taken from Ref 42, Tyler et al, *Photographic Science and Engineering*, Vol. 7, No. 5.

Fig. 5-14.

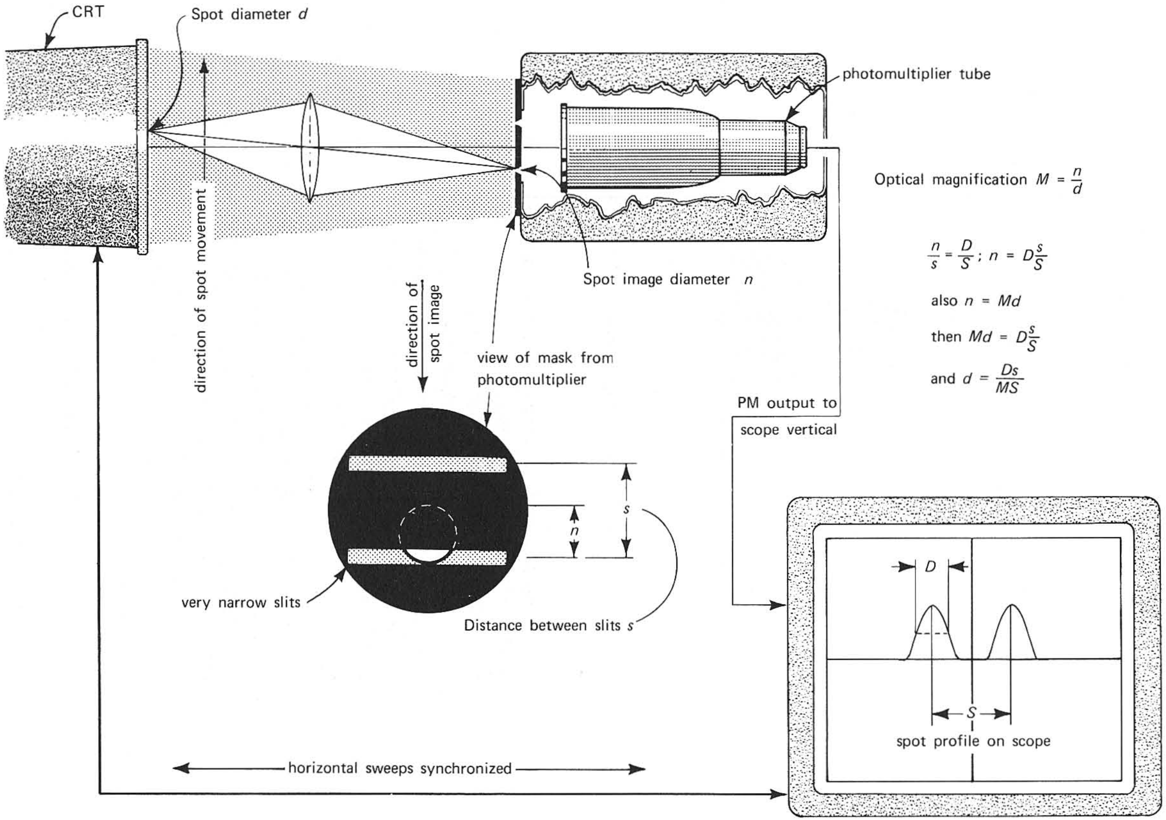


Fig. 5-15. Two-slit method of determining trace width.

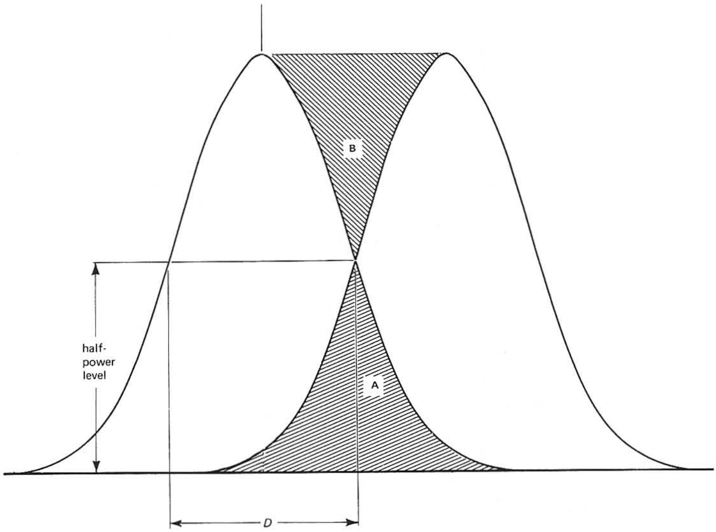


Fig. 5-16. Trace width established by shrinking raster.

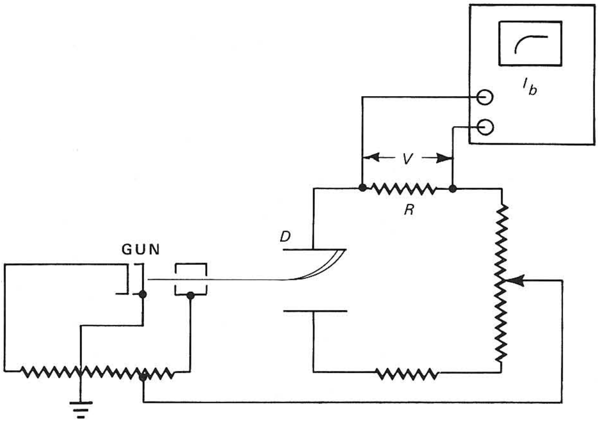
trace width

Trace-width measurements can be made by direct visual means with a telescope and reticle for approximate data. For accurate data, more sophisticated means have been devised. Fig. 5-15 illustrates the two-slit method described by Christiansen and Donaghue. Most measurements are made by the shrinking-raster method because of convenience and repeatability. In Fig. 5-16, two identical distribution curves are gradually brought closer until the area (A) included under both curves equals the area between (B), excluded by both curves. The amplitude of their intersection establishes the half-power level. The width of the curve at this point is accepted as the trace width. In practice, orthogonal rasters are displayed, using 11 lines each. The display is shrunk by reducing the voltage on the *H* and *V* ramps until the individual lines cannot be discriminated. At that point, the total width of the raster is measured; the result, divided by 11, is the measured trace width.

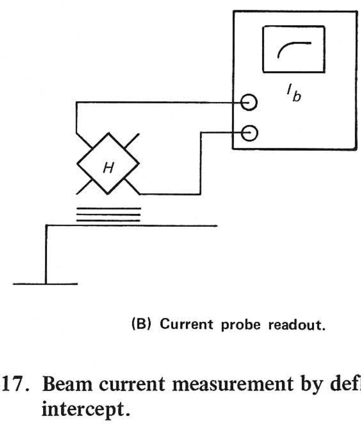
beam current

The measurement of beam current cannot easily be done by direct methods in a post-deflection CRT because actual beam current is not isolated in any available conductor. It is possible to buck out the current in the helical winding and retrieve beam current, but the work must be done at high voltage, which is awkward. A more satisfactory method was reported by Christiansen and Donaghue at the SPSE Symposium on Photography of Electronic Display, October 1962. A resistor is placed in series with a vertical deflection plate; the beam is directed into the plate by the positioning control, and the current determined from V/R (Fig. 5-17). A measurement is also made at the other plate to avoid errors of symmetry. It is necessary to use an oscilloscope as an indicator because beam current is not constant enough thoughout the sweep cycle to measure with a meter; by using a scope, the current can be measured during the constant-rate sweep period.

Performance curves for T5470, Figs. 5-18A and B, illustrate the relationship between beam current and trace width. When the data are translated to a linear graph, (C), the curve is seen to be remarkably straight. This implies constant beam-current density.



(A) Voltage drop readout.



(B) Current probe readout.

Fig. 5-17. Beam current measurement by deflection-plate intercept.

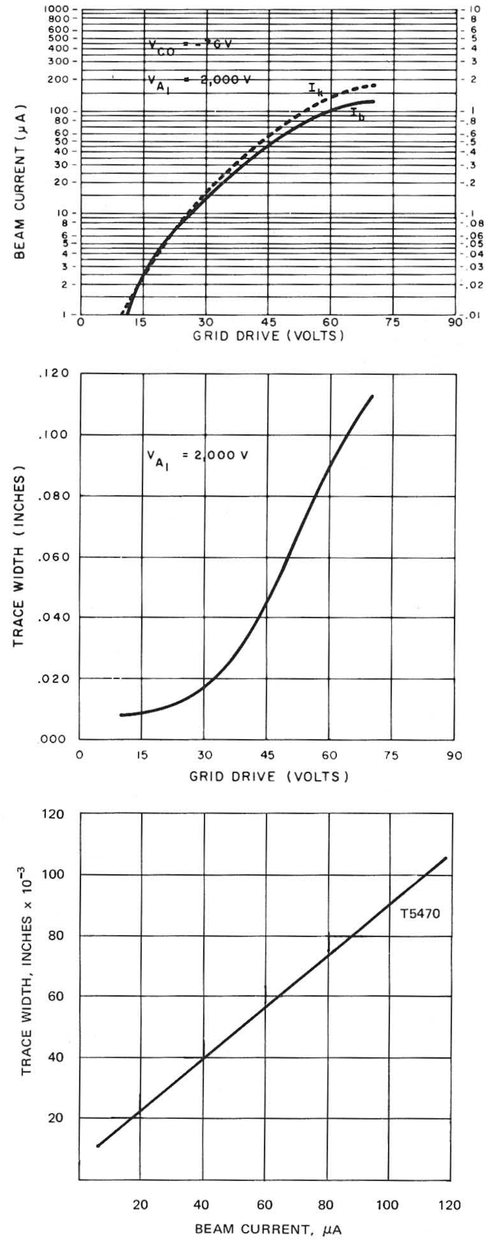


Fig. 5-18. Curves inferring beam-current density. The bottom curve is derived from the other two.

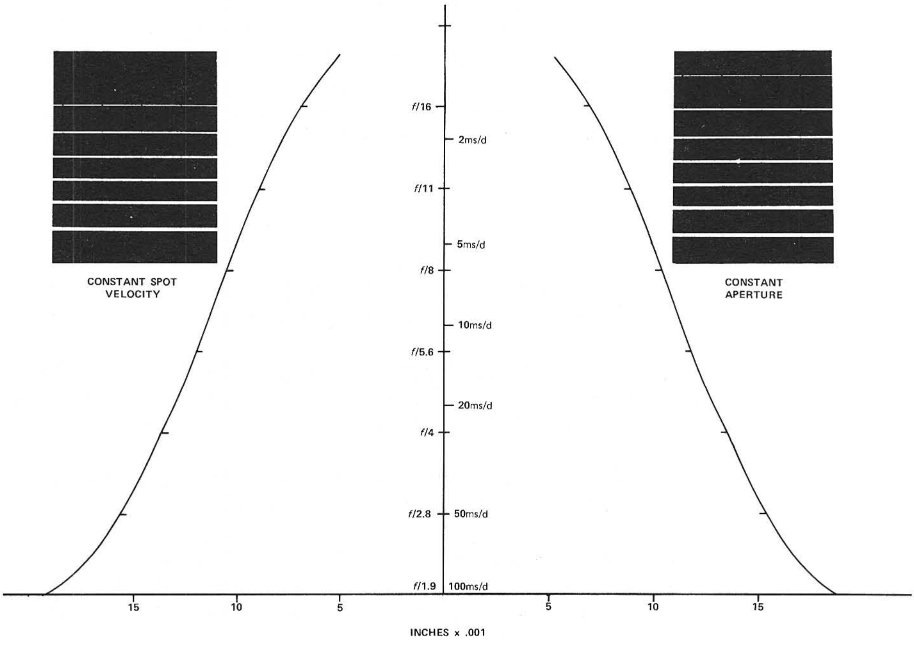


Fig. 5-19. Recorded trace width versus lens aperture and versus inverse trace velocity; beam current constant.

Fig. 5-19 is the result of a simple experiment comparing recorded trace width with spot velocity and with exposure varied by indexed aperture stops. The spot is well-focused and beam current is constant. The individual records of the trace imply a series of planes passed through the distribution curve of beam power versus trace width. The resulting curve is the power-density profile of the moving beam. Note the parameter is *trace width* rather than spot size; the trace describes the record of the moving beam of electrons. The visual or photographic record results from energy delivered per unit area; that is, power per unit area per second. The *dwell time*, the period the beam covers one spot-size area of the phosphor, is the trace time per unit distance, divided by trace width (in same units):

$$t_D = \frac{t}{ld}$$

With no vertical component, t/l is sweep time per division. The factor, dwell time, has the dimensions of time per unit area.

As the CRT beam traverses any particular area of the faceplate, the phosphor receives a charge of $I_B \cdot t_D$ coulombs per unit area, and the energy received is $V_A I_B t_D$ joules per unit area.

It should be evident from these expressions that beam-current density decreases with increasing spot velocity.

As an example, using the curves of Fig. 5-18, examine one excursion of a trace written at 100 cm/ms, with a beam current of 40 μA. Trace width (Fig. 5-18C) at this current is 0.04 inches, or one millimeter. The dwell time is:

$$\frac{10\ \mu s/cm}{.04 \cdot 2.5} = \frac{10 \cdot 10^{-6}}{0.1} = 10^{-4} \text{ seconds}$$

The charge per unit area is:

$$t_D \cdot I_B = 40 \cdot 10^{-6} \cdot 10^{-4} = 4 \cdot 10^{-9} \text{ coulombs per square centimeter}$$

$$\text{Energy density} = V_A I_B t_D = 10^4 \cdot 4 \cdot 10^{-9} \text{ joules per square centimeter}$$

$$= 400 \text{ ergs/cm}^2$$

Notice that V_A here is the total accelerator voltage. The V_A noted on the curve applies to the first anode.

5.8. DISPLAY EFFICIENCY*

The energy delivered to the phosphor is:

$$J_b = \frac{V_a I_b \cdot t}{d \cdot l} = \text{joules (watt seconds) per unit area}$$

V_a = volts from cathode to final anode

I_b = beam current during trace traverse

d = average trace width

t = time of sweep traverse

l = length of sweep traverse

This expression is mathematically identical to that in the previous section.

Note that if there is no vertical component in the display, t/l is the scope time-base setting.

After applying a phosphor loss factor ϕ, the radiance at the faceplate is:

$$J_\phi = \phi \frac{P_b \; t}{d \;\; l}$$

To express the energy in radiation exposure units, ergs per square centimeter, express d and l in centimeters and multiply the result by 10^7. *Erg* is a more convenient unit than is *joule* for these small energies.

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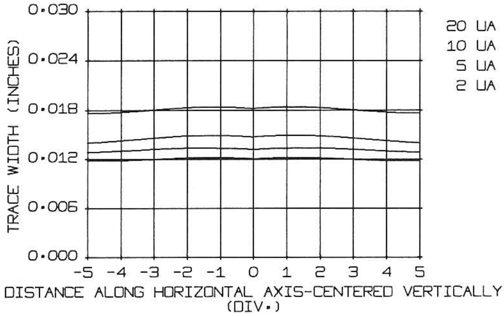
*Ref: 2. Beiser
4. Bryden

The phosphor efficiency factor, ϕ, lumps all the loss in converting beam energy to radiance into one factor:

Element	Depends on	% Loss	Maximum efficiency, %
Aluminum backing	Thickness, process, V_a	10-20	90
Phosphor mechanics	Thickness, process, V_a	20-50	80
Miscellaneous	Reflection & spectral absorption	3-5	97
Phosphor luminescence	Composition & particle size	80-99.9	20

The product of the four categories is in the range of 12-15%. For any particular process the greatest variations result from the characteristics of the phosphor itself. The factor ϕ is concluded from measurements made from the outside surface of the faceplate, and so includes all losses to that point. Note that the curves of Fig. 5-12 are useful only to compare luminescence values rather than radiant flux.

ALL TRACE WIDTH MEASUREMENTS TAKEN USING SHRINKING-RASTER METHOD WITH 11-LINE RASTER AT 2KHz REP-RATE.



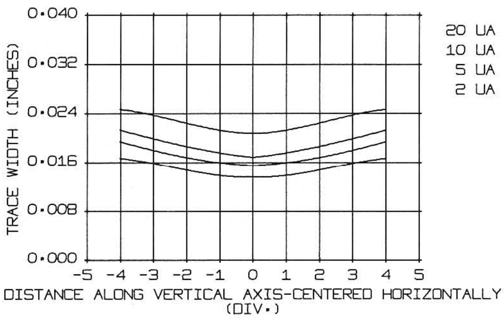


Fig. 5-20. Trace width at points on horizontal and on vertical axes.

5.9. ABERRATIONS*

General performance of a CRT is usually optimized in the center of the scan and falls off at the extremities, similar to the behavior of lenses.

trace width versus spot position

The curves of Fig. 5-20 show how trace width changes with spot position. If the spot is adjusted to be circular at the center of scan, it will be slightly elliptical in all other areas.

deflection plate intercept

Deflection-system design permits part of the beam to strike the deflection plate at the scan extremity. The result is a proportional loss of power in the beam. The effect is more pronounced in the vertical direction, as indicated in Fig. 5-21.

*Ref: 30. Radiation Lab, Ch 2

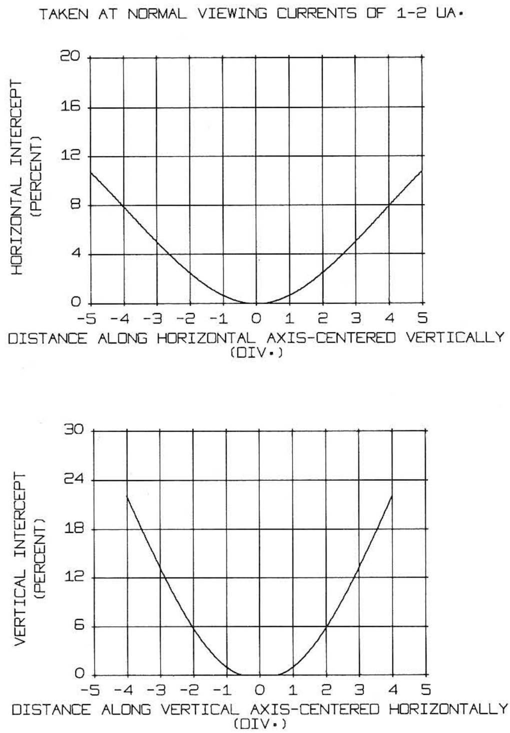


Fig. 5-21. Percent interception of beam current at points on horizontal and vertical axes.

nonlinearity

Another characteristic that might occasionally be of consequence is the loss of deflection linearity at the extremes of scan. As indicated by Fig. 5-22, the nonlinearity is barely measurable on the CRT face. The deflection circuitry is usually designed to compensate for deflection nonlinearity.

Geometrical distortion results from electrostatic distortion of the electron lens as the beam passes close to the deflection plates. Also, the distance from deflection plates to faceplate increases at the scan extremities, causing defocusing at the extremities of scan.

barrel or pincushion

Another result of the changing path length is barrel or pincushion distortion, analogous to the same effect in optics. Shaping of the deflection plates corrects this effect.

orthogonality

Physical misalignment of the deflection-plate pairs introduces orthogonal distortion, which may cause appreciable error in rise-time measurements. Some distortion is evident only at scan

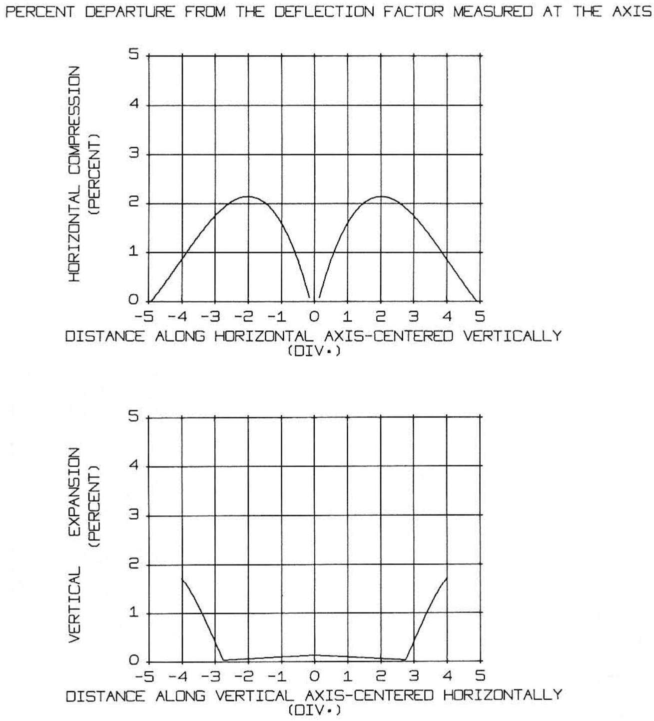


Fig. 5-22. Departure from deflection linearity.

extremities and incurs esthetic disappointment but measurement error is not significant.

visible noise

Noise may arise in the CRT from the heater of the cathode. Visible radiation from the cathode is relatively small, but if the camera shutter remains open awaiting a signal, *cathode glow* may contribute unwanted response on the film if the CRT is not sufficiently aluminized. Secondary-emission radiation, resulting from beam electrons striking metal members of the assembly or the conducting surface of the envelope, may cause undesired exposure. In glass-envelope CRT's, ambient light may be conducted by the envelope to the faceplate.

Other possible noise sources are corona from sharp metallic points anywhere in the high-voltage circuit, radiation from the high-voltage oscillator, noise from the unblanking circuit, and errors in unblanking-signal rise characteristics.

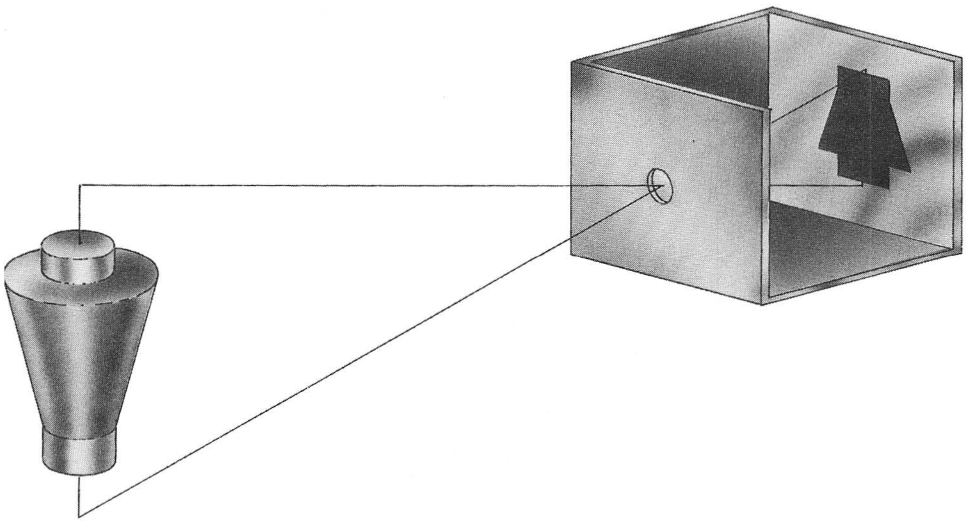


Fig. 6-1. Pinhole camera.

6

CAMERAS

This chapter is a review of cameras in general, as a basis for the more particular subject of oscilloscope cameras. More extensive and authoritative texts on cameras are listed in the references.

The simplest camera conceivable would be a light-tight box with a piece of film attached to the inside surface of one face, and a small hole in the opposite face (Fig. 6-1).

The three essential features of a camera are:

- A means of holding the sensitized film flat, in unexposed condition.
- A means for bringing the image to a focus on the film surface.
- A means for metering the light coming from the object.

6.1. HOLDING THE FILM*

flat and unexposed

Holding the film flat and unexposed isn't so easy to do; criteria for depth of focus noted in Chapter 4 indicate how flat the film must remain. Data on film sensitivity from Chapter 3 indicate the light-tight security necessary. The problem is how to maintain these criteria, yet be able to change film rapidly. Photographic exposures made on glass plates have flatness and dimensional stability but are not convenient.

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*Ref: 27. Neblette, Ch 7

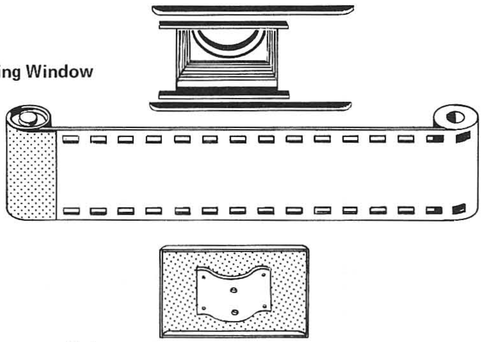


Fig. 6-2. Preserving a flat image plane with roll film.

roll film

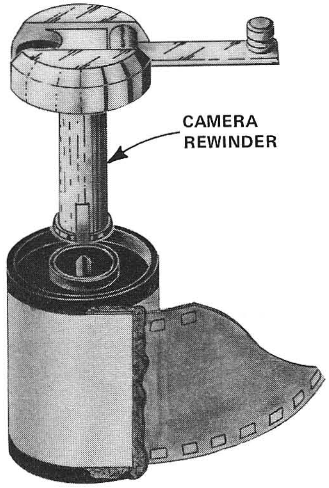
The most convenient and most popular form of wet-process film is in rolls. Most roll films are rolled up on a spindle with black backing paper. As the film is unrolled for exposure, the portions not being exposed are protected. The emulsion side of the film, facing the lens, is drawn across a window which is held at a fixed distance from the lens. A spring-loaded backplate that presses against the black paper traveling with the film holds the film flat and normal to the lens axis (Fig. 6-2). For the system to work well, the film must be fairly thin (.005″) and under slight tension.

cassettes

Cassettes, or light-tight cylinders, are used for some small format films, such as 35-mm (Fig. 6-3A). The film is originally rolled up on a spool without any protective paper and enclosed in a cassette with a light-insulated slot through which the film is drawn. The cassettes have also an opening in top and bottom so the spool ends can be used as a bearing, and so the spool can be removed after the roll is exposed.

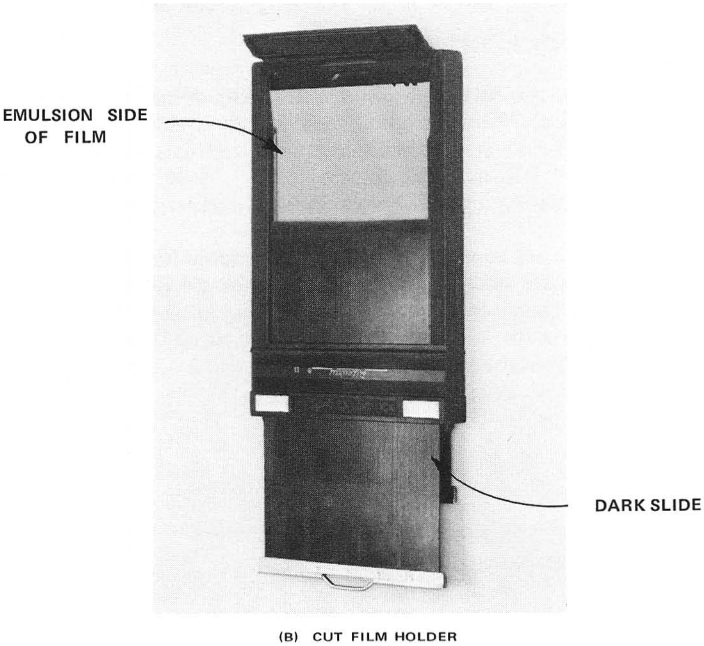
cut film

Before the days of 35-mm still cameras, practically all commercial photography used individual sheets of film, usually referred to as cut film. Cut film is prepared by sliding each sheet into a metal-backed carrier that provides a window for exposure and a dark slide to protect the unexposed film. (Fig. 6-3B). For exposure the holder is fixed to the camera back, the dark slide is removed, exposure is made, and the dark slide is replaced. Then the holder



35mm cartridge

(A) POPULAR FORM OF FILM CASSETTE



(B) CUT FILM HOLDER

Fig. 6-3.

is set aside for processing. Flatness is preserved by the metal back, the metal guides at the edges, and by the stiffness of the film itself, which is thicker (.010″) than roll film.

glass plates

Glass plates are still required for all work where dimensional stability is essential, such as astronomy and spectroscopy, also the new fields of integrated-circuit replication. In any case, the back of the camera will be designed for a particular film format; often provision is made to change camera backs to accommodate different formats. For example, cameras designed for 4 x 5 (inches) cut film will also take a special back for Polaroid 4 x 5 packs.

6.2. LENS CHARACTERISTICS*

design

An exercise to find numbers for a hypothical lens design might begin with the required size of the image and the maximum size of the object; this provides image-to-object ratio, M (Fig. 6-4). The maximum allowable working distance will approximate $(u + v)$. If the working distance chosen is very short, the semifield angle, $\arctan \frac{y'}{v}$, will be large, and astigmatism and distortion will increase (Chapter 4).

"normal"

There is a rule of thumb for choosing a "normal" lens for a particular film format – focal length equals image diagonal. This results in a semifield angle at infinite focus whose tangent is $y'/f = 1/2$, or a half angle of 26.5°. Most amateur cameras are sold with a lens of corresponding focal length.

criteria

There are so many lens designs available for photographic purposes that only unique applications require a new design, and even then adjustments to an existing design may be adequate. The criteria for image quality should be listed in order of priorities, and limits established so major criteria can be optimized at the expense of minor criteria.

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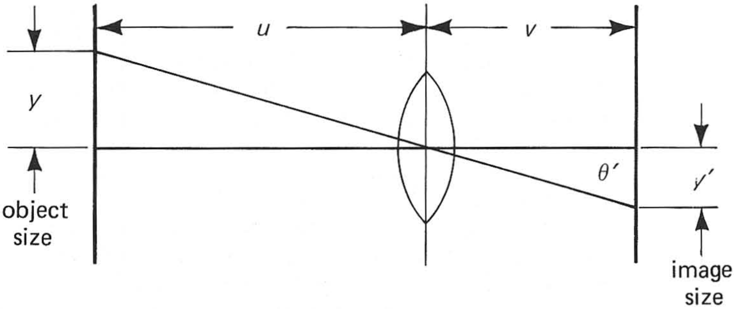
*Ref: 27. Neblette, Ch 5
5. Cox
35. SPSE

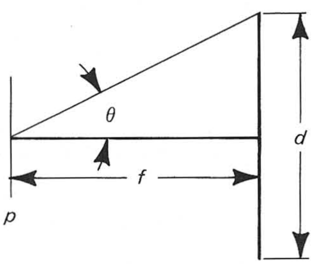


Magnification: $M = \frac{y'}{y} = \frac{v}{u}$

Working distance: $u + v = f(2 + M + 1/M)$

Focal length: $f = \frac{u + v}{2 + M + 1/M}$

Field angle: $\tan \theta' = \frac{y'}{v}$



θ = half the field angle
p = rear principal plane
d = diagonal of film
f = focal length, and image distance at infinity

$\tan \theta = \frac{\frac{1}{2}d}{f}$

when $d = f$
$\tan \theta = 0.5$, $\theta = 26.5^\circ$ and field angle = 53°

Fig. 6-4. Working distance and field angle.

6.3. FOCUSING AND FRAMING*

focusing mechanisms

Hand-held cameras are focused by adjusting the distance between the lens and the film plane. The range of adjustment is usually from infinite focus to $M = 1/10$. The lens element is moved axially by rotating about the lens a cylinder with a helical slot that engages a pin in the lens barrel. Studio cameras, view cameras, some process cameras provide position adjustment for both lens plane and film plane. The range of focus can be from infinite to $M > 1$. The adjustment is usually made by a rack-and-pinion drive. Process cameras, used in commercial printing, have calibrated settings for magnification and focus. For extremely precise work, where focus for optimum resolution may not be the same position defined by optical focus, a series of pictures is taken at accurately measured focus positions; the pictures are then evaluated for modulation transfer index (Chapters 3 and 4), and the optimum focus position is recorded.

coupled rangefinder

The coupled rangefinder works by triangulation, the same principle by which the eye provides depth perception. If a half-silvered mirror is established 45° to an optical axis and another mirror placed 45° to an axis removed from the first by several inches, an eye focused on a distant object will see two objects. By changing the angle of one mirror slightly with respect to the other, both objects will appear to merge into one (Fig. 6-5). By measuring the angle at known distances, the rangefinder is calibrated. For camera use, the axial focusing movement of the lens is mechanically coupled to the rotating mirror. A change to a lens of different focal length requires a change in the coupling linkage.

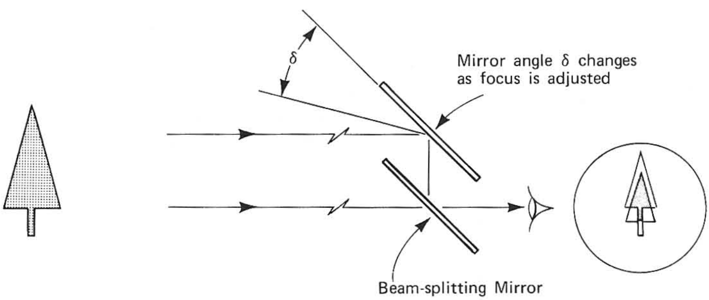


Fig. 6-5. Idea of coupled rangefinder.

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*Ref: 27. Neblette, Ch 7
5. Cox
37.5 Schwalberg

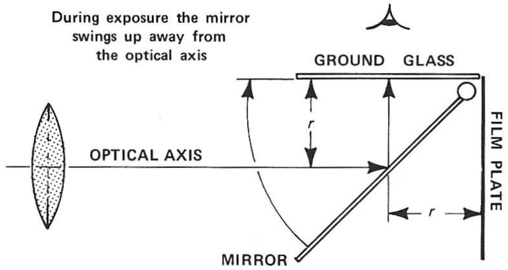

Fig. 6-6. Principle of single-lens reflex camera.

single-lens reflex

By observing the object on a ground-glass screen whose surface is at the image plane directly, or by reflection, the point of focus is determined visually (Fig. 6-6). By this means focusing and composing are done in one visual operation. This SLR (single lens reflex) system has several advantages: Lenses of different focal length may be used without affecting the focusing procedure; the effect on focus of stopping down the lens may be observed; and exposure meter can be incorporated behind the lens, so that a change in aperture or addition of a filter is accounted for by the meter.

The SLR solution introduces another problem – that of keeping the VIEWED image erect and oriented. A pentaprism with roof is often used to provide the correct number of reflections so that the viewfinder presents the same view seen by the naked eye, regardless of the position of the camera (Fig. 6-7).

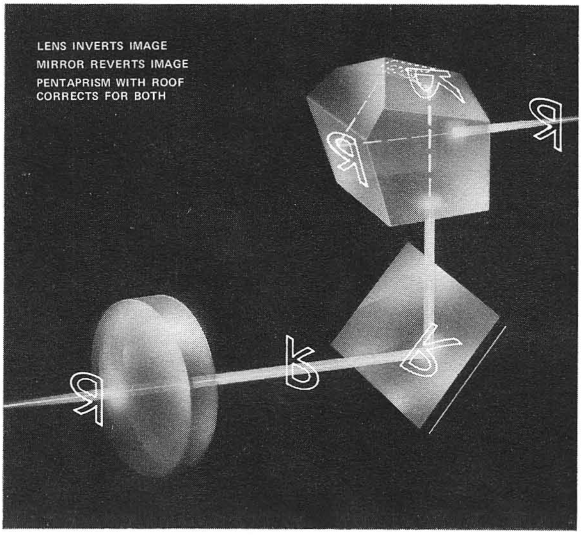

Fig. 6-7. Pentaprism arrangement for viewing object erect and correct.

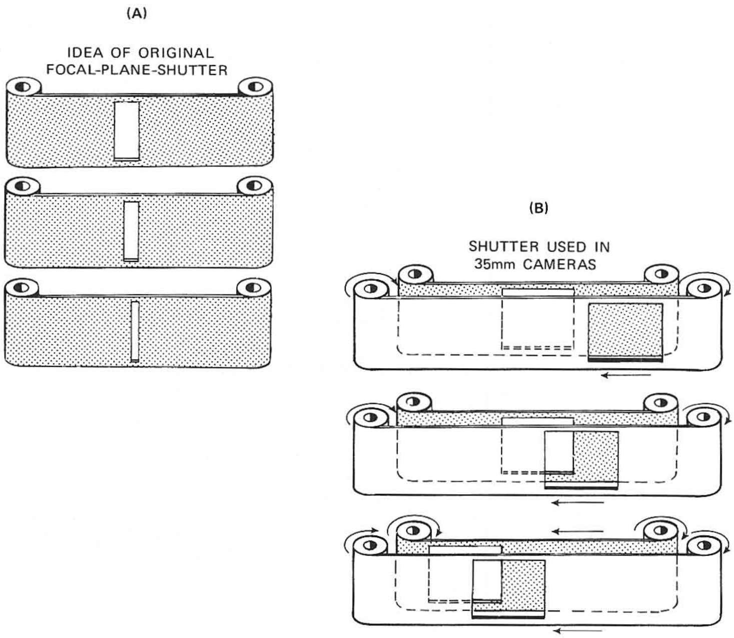

Fig. 6-8. Focal-plane shutters.

6.4. SHUTTERS*

The *shutter*, the light-metering device, is essentially the on-and-off switch for light. The shutter is often mounted between lens elements, along with the variable-aperture or adjustable stop.

focal plane

The focal-plane shutter was originally developed for commercial cameras with a 4 x 5 or larger format. This shutter effectively moved a slit across the film plane, allowing the film to be exposed progressively from one end to the other. The amount of exposure was determined by the width of the slit and its speed of travel (Fig. 6-8A). A similar system is now used on 35-mm cameras that allow interchangeable lenses. Usually, two independent curtains are used; one covers the film before exposure and is drawn away during exposure. The second curtain is originally rolled up and follows the first across the film to finish the exposure. As the exposure time is made shorter, the closing curtain begins to follow the opening curtain more closely until an actual slit is moving across the film plane (Fig. 6-8B).

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*Ref: 27. Neblette, Ch 6
1. ANSI (d)

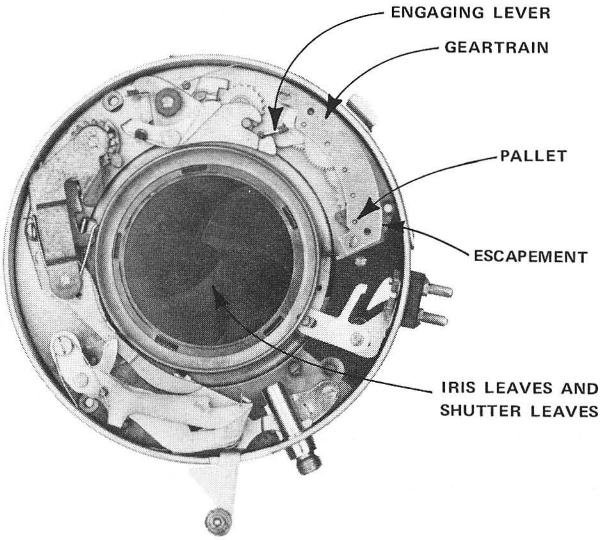

Fig. 6-9. Between-the-lens shutter.

between-the-lens

Between-the-lens shutters (Fig. 6-9) are of clock-works design. A cocking device stores energy in a spring. When the trigger is released, an arm transfers the energy to the first gear of a high-to-low gear train. The amount of energy transferred is controlled by the point at which the arm engages the first gear. The gear train ends in a pallet-and-ratchet assembly, which dissipates energy at a constant rate. The time required for the event depends then on the number of revolutions made by a particular gear, which is set as indicated above. Electrically-timed shutters are discussed in Chapter 7.

There are two exposure time aberrations that occur in between-the-lens shutters. When exposure time is long, say one second, there is no concern about the time required for opening and closing, but when exposures are in milliseconds, both the reaction time and the changing size of the opening in transition determine the actual exposure (Fig. 6-10). The opening and closing time may each be more than 2 milliseconds. Note also that a small lens opening is uncovered and covered much more quickly than is a large lens opening, consequently, with a fast shutter speed, the exposure will be longer for small apertures than for larger apertures.

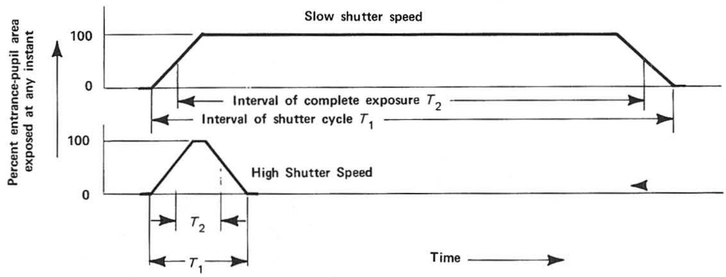

Fig. 6-10. Shutter speed error.

6.5. THE EXPOSURE EQUATION*

Exposure control is effected by adjusting conditions to satisfy the exposure equation:

$$E_x = \frac{\pi B \cdot T}{4\, A^2 (M+1)^2} \, (t) \qquad \text{(Eq. 6-1)}$$

Exposure, E_x, represents the quantity of energy available per unit area of the image.

luminance

transmission factor

Luminance, B, is light available from the object in footlamberts (if reading is in candles per square foot, B_o must be multiplied by π). Transmission factor, T, lumps the lens losses for small field angles (Chapter 4).

aperture

magnification

The aperture, A, is the apparent *f*-stop, indicated on the lens. For most photography, the image-to-object distance is more than 10 focal lengths, and M is less than 0.1, so the actual *f*-stop is very little more than the apparent *f*-stop. For shorter distances the indicated aperture should be multiplied by $(M + 1)$ to provide the actual aperture.

film speed

The film speed, S, is usually the ASA speed, rated by the manufacturer, as discussed in Chapter 3.

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*Ref: 27. Neblette, Ch 8
1. ANSI (a)

time

Exposure time, t, is usually the length of time the shutter is open. In some applications the shutter is left open, and the exposure is timed by the period of illumination, such as that from a flashbulb or a single trace on an oscilloscope.

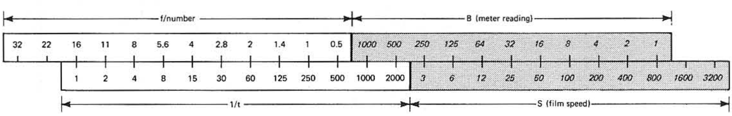
When we are about to make an exposure, the only factors of the equation that can be altered are S, B, A and t. All the other factors can be considered constant, and are included in the factor K. Equation 6-1 then reduces to:

$$A^2 \frac{1}{t} = S \frac{B}{K} \qquad \text{(Eq. 6-2)}$$

Obviously, the equation can be restated to find any one factor in terms of the others. Since film speed is fixed for the film we have in the camera, and the light has been measured, we can only control aperture and time. Usual practice, then, is to adjust A and t to satisfy the equation.

exposure meter slide rule

Fig. 6-11 expresses the exposure equation in the form of a slide rule; the same arrangement is part of the common exposure meter, but laid out in circular form for convenience. When the meter reading is set opposite the film speed, all the appropriate combinations of f/number and shutter speed are aligned.



$$A^2 \cdot \frac{1}{t} = B' \cdot S \qquad \text{(Eq. 6-3)}$$

where:

A = f-number
t = shutter speed
S = ASA film speed
B' = luminance B, divided by a factor K that accounts for assumed lens losses and source spectral influence.

The scales on exposure meters are constructed on this pattern.

Fig. 6-11. Slide rule for solving the exposure equation.

incident light measurements

The K in Equation 6-2 accounts for lens losses, flare, vignetting, and M, accumulated and arbitrarily fixed as a standard for manufacturers of exposure meters. K takes different values, depending on the measurement system used and spectral distribution of the source. When incident-light measurements are used, as discussed below, the factor becomes C, and includes a factor assuming an average object reflectance of about 16%. American National Standard PH2.12 defines the terms and factors used and acceptable methods of testing. Equation 6-2 then becomes, for incident light:

$$A^2 \cdot \frac{1}{t} = S \cdot \frac{I}{C} \qquad \text{(Eq 6-4)*}$$

where I is illuminance (incident light) in footcandles and C is a constant, arbitrarily fixed somewhere between 16 and 28, depending on the arrangement of the light-measuring system.

If we set the products on either side of Equation 6-3 equal to the exponential 2^{E_v}:

$$A^2 \cdot \frac{1}{t} = B' \cdot S = 2^{E_v},$$

and convert to base-2 logarithms, then:

$$2 \log_2 A - \log_2 t = \log_2 B' + \log_2 S = E_v \log_2 2 = E_v;$$

Now if we express the elements of the equation 6-3 as logarithms:

$$A_v = 2 \log_2 A$$
$$t_v = \log_2 (1/t)$$
$$S_v = \log_2 (0.35)$$
$$B_v = \log_2 B'$$

Then $A_v + t_v = B_v + S_v = E_v$, which provides much more convenient computation.

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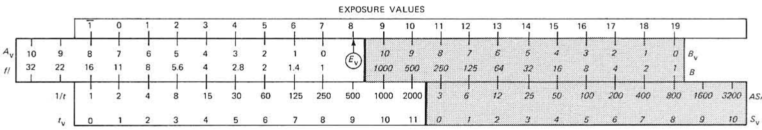
*Properly, E is the symbol for illuminance, but we need to avoid confusion with the E used for *exposure*.



$$\frac{A^2}{t} = \frac{BS}{K} = \frac{IS}{C} = 2^{E_V} \qquad A_V + t_V = B_V + S_V = I_V + S_V = E_V$$

Fig. 6-11A.

Fig. 6-11A shows an extension of the slide rule of Fig. 6-11, providing exposure values, E_V. When the log values of the several factors are memorized, the computation requires only addition and can be done mentally. Notice that the illustrated slide rule is set for an E_V value of 8. On the left side, each of the matching A_V and t_V figures add up to 8; this means that any matching combination of aperture stop and shutter speed will satisfy the equation. An increase in exposure value implies either that more light has become available or that a higher film speed has been assigned. To adjust for this increase, the time or the aperture must be decreased accordingly.

2^{E_V}

The E_V numbers are all powers of 2, convenient to use by binary arithmetic or binary electronics. The sum of the logs of film speed and light is the exposure value, E_V; any combination of A_V and t_V that adds up to E_V will satisfy the equation.

reflected light

Exposure meters, sometimes termed light meters, use one of two methods to determine required exposure. The reflected-light method places the exposure meter at the camera, pointing toward the subject; the light reflected from the total scene subtended by the solid angle at the exposure meter is integrated. If much sky or snow is included in the subject seen by the exposure meter, the subject will be underexposed. If the object is available to the photographer, he may get close enough to evaluate different areas of the subject selectively and adjust his exposure accordingly. Some meters make narrow-beam measurements so critical areas of the subject can be measured separately.

incident light

When the incident-light method is used, the meter is held at the object, facing the camera; it reads the illuminance falling on the object, rather than the light being reflected. The photographer may then adjust the exposure to allow for unusually low or high object reflectance, or background reflectance.

6.6. METERING SYSTEMS*

through-the-lens

One of the conveniences of the single-lens reflex camera is *through-the-lens metering.* If the light measurement is made through the lens, there are no computations necessary for filters or *f*-stop; when the indicating needle seen in the viewfinder is within the proper range, the exposure equation is satisfied.

semi-automatic

While there are numerous variations, the design provides a photocell (usually cadmium sulphide, CdS) fixed in the optical path of the viewfinder; this meter does not read luminance values, but indicates a balanced condition of the electronic exposure computer, in response to preset conditions. The film speed is preset by the operator; this setting establishes the S-factor in the equation, either by circuit compensation or by adjusting the meter movement itself. Next, the exposure time is set; this provides another adjustment to the circuit. The operator adjusts the *f*-stop until the light flux through the lens satisfies the equation, and the needle so indicates. In this way the final two factors, aperture and luminance, are included to complete the equation. Of course, it is often appropriate to preset the *f*-stop and adjust the exposure time to balance the equation.

automatic

Some cameras provide completely automatic exposure by controlling aperture and time electromechanically. The operator need only to frame, focus, and respond to a go-no go indicator.

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*Ref: 37.5. Schwalberg

6.7. LIGHT FILTERS*

Light filters are essentially light attenuators and can be classed as nonselective (neutral density), selective (color correcting) and polarizing.

neutral density

Neutral-density filters are not often needed in photographic exposure; their principal use is to reduce the overall light without discriminating against any particular wavelength. Photometers and densitometers use neutral-density filters calibrated in density steps. In some phosphors the unexcited CRT reflects enough ambient light to degrade visual contrast with the trace; a neutral-density filter placed over the CRT provides a dark background for the CRT trace. This arrangement has no value with an oscilloscope camera, but may be needed for a photograph of the complete oscilloscope, including the trace.

color selective

The term *light filter* usually refers to color-selective filters used in photographic applications as well as photometry, microscopy and other optical work. For black-and-white photography, a number of standard filters are available to attenuate certain colors, depending on the response of the film used and the effect desired. Other filters used for color photography compensate for different sources of light so that color values in the picture approximate more closely what appears natural.

The filters used in photographic processing for publication must provide precise control of hue and saturation.

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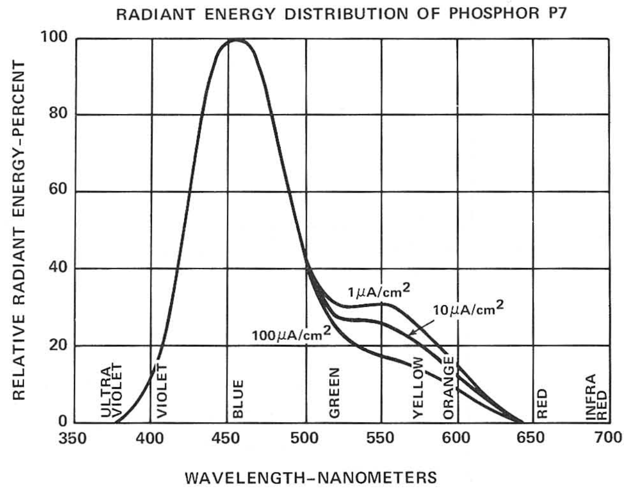
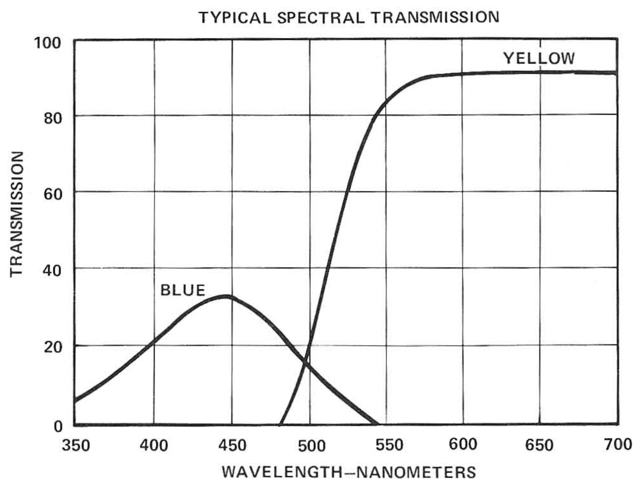
*Ref: 21. Kodak, (b), (d)
27. Neblette, Ch 3
26. Monk, Ch 8
14. Hardy and Perrin, Ch 29



(A)



(B)

Fig. 6-12. Using a blue filter to attenuate the phosphorescence from P7 phosphor.

Of particular interest for oscilloscope work are filters to pass or reject light from the several CRT phosphors. An example is the P-7 phosphor; the distribution curve is shown in Fig. 6-12A. Radiation in the blue region is fluorescent, it decays very rapidly; the phosphorescence, in the yellow region, may last for seconds. When the phosphorescence produces a smearing effect on the picture because of its long persistence, a blue filter with the response shown in Fig. 6-12B can be placed over the CRT face to attenuate the unwanted yellow radiation. Conversely, the blue can be attenuated with a yellow filter.

polarizing

Another important group of filters are those that depend on the polarization of light (reviewed in Chapter 2). Polarizing filters are usually made by applying a dichroic polyvinyl material to an acetate or acrylic plastic base. When the polyvinyl material is processed under physical stress, it becomes refraction-oriented and passes only that portion of the light vibrating in the accepted plane. The amount of polarization can be controlled to some extent by the materials and processing; wavelength selection can also be included. It is important to remember that the unpolarized light is absorbed, and the filter insertion loss will increase with the effectiveness of the polarization.

plane polarization

The polarizing filter is a very effective tool in optical work, including photography. Reflections from all nonmetallic, specular (mirror) surfaces are polarized in a plane parallel to the reflecting surface. The filter can be oriented in a manner to absorb the reflection, or to pass the reflection and absorb the other radiation. Two plane-polarizing filters may be used as a continuously-variable neutral density filter by adjusting the rotation orientation of one with respect to the other. Attenuation of more than 40 dB (a density difference of 4.0) can be effected by this means. Plane polarized filters are used in commercial photography. When a subject is illuminated for the desired light-and-shadow balance, there are often objectionable highlights from shiny surfaces. If the light source is plane-polarized by a filter, another filter can be placed over the lens, and oriented to eliminate the reflections (Fig. 6-13).

circular polarization

Circular polarization can be imparted to light by first passing it through a plane polarizer, then through a quarter-wave plate of birefringent plastic material which results in two wavefronts, polarized in opposite directions, but with one delayed by a quarter wave ($\pi/2$ phase shift). The resulting wavefronts are now complex, one having a progressive quarter-wave phase shift either leading or lagging, depending on the orientation of the quarter-wave retarder plate with that of the linear polarizer. The implication is a wave train whose plane of amplitudes is twisting in space, describing a helix. Light passing through this filter and striking a reflecting surface, will have its pattern of rotation reversed, and will always return to the filter in a plane 90° from the original polarization; consequently it will be absorbed by the filter.

This type of filter is often effective in reducing reflection of ambient light from the CRT faceplate (Fig. 6-14).

6.8. CHANGING THE EFFECTIVE FOCAL LENGTH*

A 35-mm camera with a lens of 50-mm focal length will usually have a focusing range that limits M to about 0.1. If an M greater than this is needed, for example to provide a 1-to-4 picture from an oscilloscope (M = 0.25), means are needed to increase the range of focus. Fig. 6-15 shows how the lens-and-camera geometry limits focus range. The back focal distance may vary from $v_0 = f$ to $v_1 = f(1 + 0.1)$; the front focal distance may vary from u_0 = infinity to $u_1 = f(1 + 10)$. To shorten u requires some means of bringing the lens forward to increase v. If the camera provides for interchangeable lenses, a small extension tube can be inserted between the lens and the camera body, increasing v mechanically to equal 1.25 f. Because the focusing arrangement provides only limited range, there will then be a finite limit to the value of u, but the close focus is accommodated.

extension tube

For those cases where an extension tube is either impossible or inconvenient, a supplementary lens may be used. The supplementary lens effectively changes the focal length of the system. The other characteristics, such as aberrations, are affected more or less, depending on the nature of the supplementary lens and that of the original; if the change of effective focal length is not very large, the increase in aberrations will be minimal. The supplementary lens is usually a single element, positive for shortening focal length, or negative to lengthen focal length.

supplementary lens

As an example, choose a popular configuration where f_1 = 50 mm and M is a maximum at 0.1, then the nearest object in focus will be $u_1 = f_1 (1 + 1/M_1)$, or 550 mm. What supplementary lens can be used to bring into focus an object 250 mm from the lens?

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*Ref: 5. Cox, p 55
27. Neblette, Ch 5

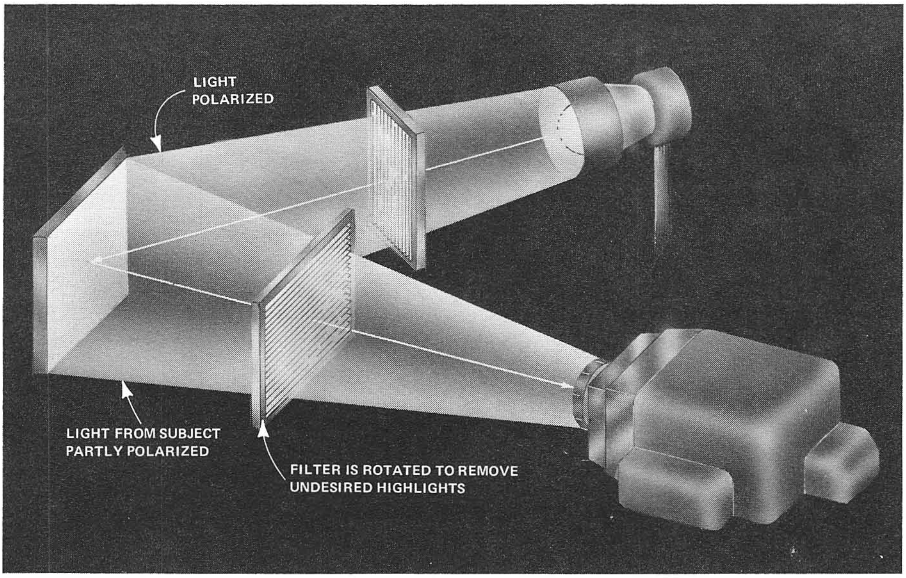


Fig. 6-13. **Use of polarizing filters to eliminate undesired reflections. Lines shown in filters indicate polarization; the lines are not actually present.**

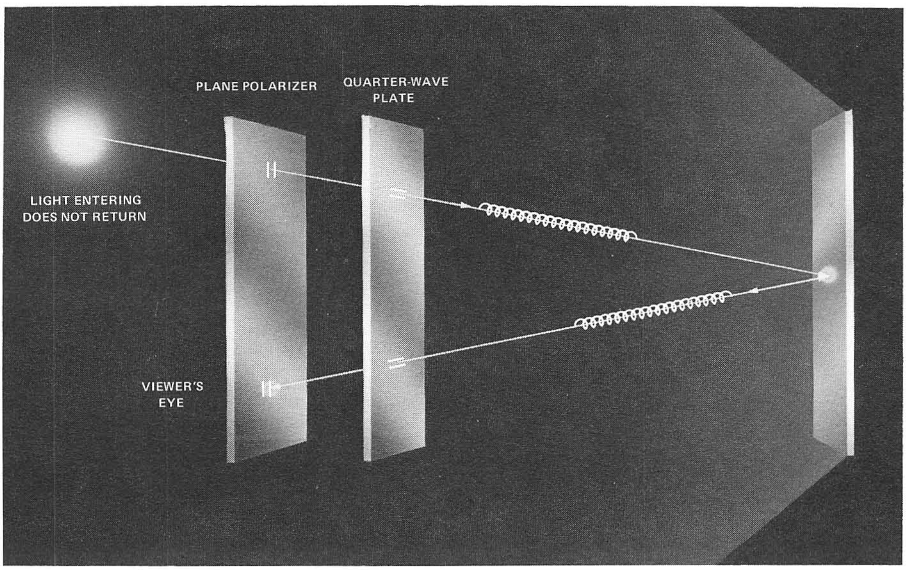


Fig. 6-14.

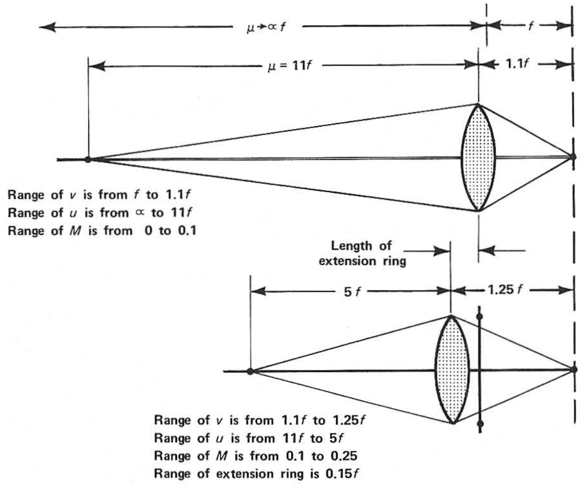


Fig. 6-15. Using an extension tube to permit focusing closer to object.

Fig. 6-16 shows ν, the rear conjugate, constant at the maximum distance permitted by the mechanical arrangement of the camera.

(1) $\nu = f_1(1 + M_1) = 50(1 + .1) = 55$ mm

For the new figure of 250 mm for the front conjugate u_0, M will have to change:

(2) $M_0 = \dfrac{\nu}{u_0} = \dfrac{55}{250} = .22$

The final equivalent focal length of the system, f_0, will be:

(3) $f_0 = \dfrac{\nu}{1 + M_0} = \dfrac{55}{1.22} = 45$ mm

The supplementary lens needed to result in the new focal length, assuming a is practically zero:

(4) $f_2 = \dfrac{f_1 f_0}{f_1 - f_0} =$ (rearrange Eq. 4-10, Chapter 4)

$$\frac{50 \cdot 45}{50 - 45} = 450 \text{ mm}$$

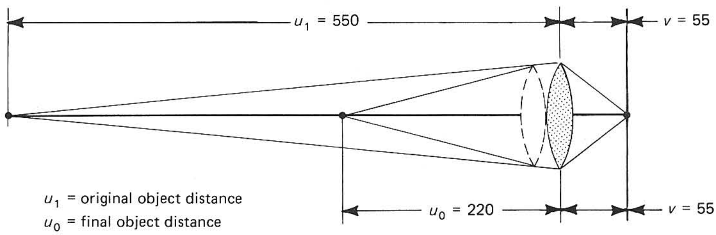


Fig. 6-16. Using a supplementary lens to bring a close object into focus.

There is a similar situation with oscilloscope cameras, where v is fixed, but we want to image some object further away; for example, the complete panel of the oscilloscope. If we want an image on Polaroid film of some object that could be included in a 13-inch diameter, we would want M to be about 0.25. If the scope camera is fixed, with v = 95 mm and the lens f_1 = 56 mm, either v must be made shorter, or f_1 must be made longer. For a temporary arrangement, it is quite easy mechanically to make f_1 longer if we are not too critical about picture distortion. Since v is fixed at 95 mm, M must be 0.25, and $v = f_1(M + 1)$, the system f must be

$$f_0 = \frac{v}{M+1} = \frac{95}{1.25} = 76 \text{ mm}$$

The focal length f_2 of the supplementary lens:

$$f_2 = \frac{f_1 f_0}{f_1 - f_0} = \frac{56 \cdot 76}{56 - 76} = -212 \text{ mm}$$

By using a simple negative lens of about $f = -200$ mm, we can bring the object plane far enough away to image the larger object. The simple arithmetic shown becomes inadequate if the principal planes of the original lens are not close together and close to where the supplementary lens can be fixed. Note again that quality of the results of this arrangement is limited, and should be evaluated by photograph before conclusions are made.

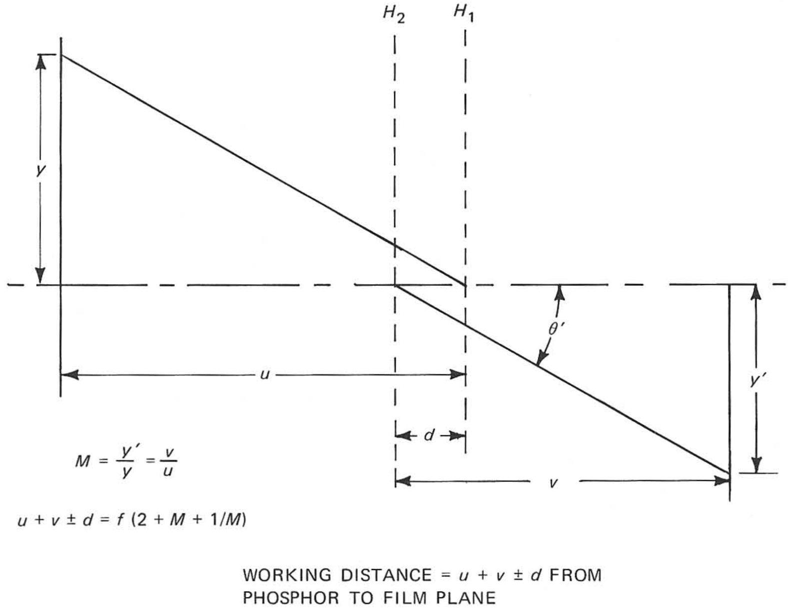


Fig. 7-1. Working distance, magnification, and field half angle.

7

FEATURES OF OSCILLOSCOPE CAMERAS

7.1. CAMERA DIMENSIONS

Early oscilloscope cameras were designed to adapt to a wide range of oscilloscopes. This was an advantage for the manufacturer as well as for the users. More recently, manufacturers introduced new and specialized oscilloscopes that require different camera approaches.

As is the case with most equipment, oscilloscope cameras are becoming more specialized. There is no way to accommodate all oscilloscopes with one camera without unreasonable compromise.

Late-design oscilloscopes have much less than half the volume and weight of their predecessors. Oscilloscope cameras are being made smaller too, but optical limitations preclude striking reductions in camera size and weight. If we look (Fig. 7-1) at the equation for conjugates,

optical limits

$$u + v = f(2 + M + \frac{1}{M}) \pm d$$

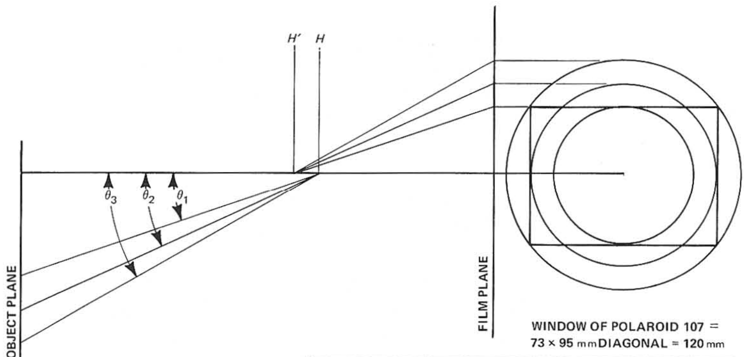
it is apparent that $(u + v)$ is a minimum when $M = 1$. When $M = 1$, the working distance is $4f$, plus or minus the small dimension between principal planes. If we attempt to reduce the length of the camera by using a shorter focal length, the field angle increases, and third- and higher order aberrations become much more troublesome.

display size

film size

Oscilloscope display dimensions range from 10 mm high by 80 mm wide to TV-picture size. The most popular size for round-face CRT's used to be 5 inches, and an 8 x 10 centimeter display area used most of the space. Since TEKTRONIX introduced the panel-space-saving rectangular CRT format, the display area is up to the oscilloscope designer. On the film size there is less flexibility because popular (and more economical) film sizes are determined by the photographic market.

Working distance and lens criteria are affected by the form factor of the film, as indicated in Fig. 7-2. There is seldom any useful information in the corners of the oscillogram, yet including the corners in the specified criteria implies poorer performance than will actually result when the critical information is centered in the display area.



θ_1 = field half angle to cover height of window

θ_2 = FHA to cover width of window

θ_3 = FHA to cover diagonal includes corners

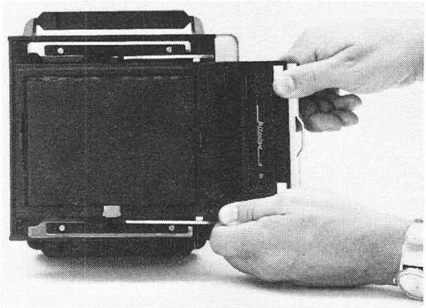
NOMINAL FILM SIZE	FILM DIMENSIONS	WINDOW DIMENSIONS	DIAGONAL
POLAROID 57	4 x 5 inches	89 x 115 mm	145 mm
POLAROID 47	82 x 106 mm	73.5 x 105.5 mm	129 mm
POLAROID 107	86 x 108 mm	73 x 95 mm	120 mm
120 roll	60 mm wide	57 x *67.5 mm	88 mm
		57 x 57 mm	80 mm
35 mm roll	35 mm wide	24 x *36 mm	43 mm
		24 x 24 mm	34 mm

*Other window lengths are also used.

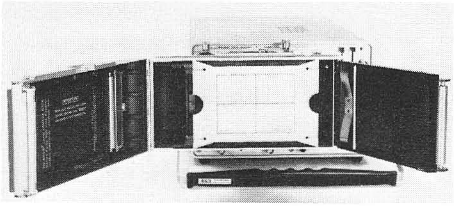
Fig. 7-2. Considerations in choosing film format.

7.2. FILM BACKS

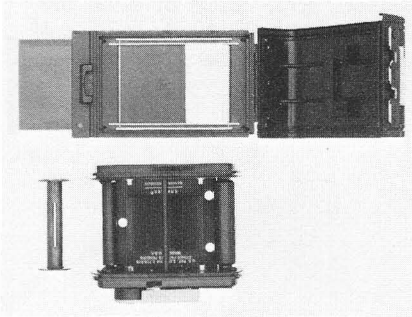
Nearly all scope cameras make the Polaroid system the first option and provide for other films and formats by interchangeable backs. Often the image-to-object ratio, *M*, is derived from the width of the 3½ x 4¼ Polaroid format (73 mm) and the height of the scope display area. The figure turns out to be something between 0.7 and 0.9. For $M = 1$, the 4 x 5 Polaroid back may be necessary. Additional conveniences are a 90° rotation option and



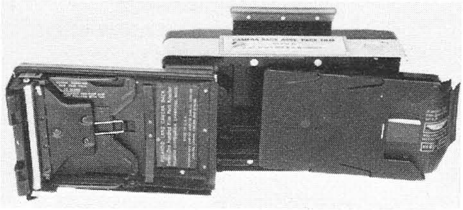
CUT FILM HOLDER GOES
INTO GRAFLOK BACK



FOCUS PLATE IN POLAROID
ROLLFILM BACK



ROLLFILM ADAPTER



POLAROID PACK FILM

Fig. 7-3. Options for film formats.

a back that can be stepped laterally to provide multiple exposures for comparison. Graflok* backs are available for cut film and also to convert to other formats such as 2¼″-wide film. Fig. 7-3 shows examples of commonly-used backs. Special cameras are made to handle 35-mm magazines for rapid-sequence exposures, and others for moving-film oscillography, where the scope sweep is disabled and the moving film provides a continuous sweep. The few requirements for these special cameras imply relatively high costs.

*Registered Trademark Graflex, Inc.

7.3. MAGNIFICATION AND FOCUS

When oscilloscope cameras have a fixed lens-to-film distance (with interchangeable lenses), focusing is accomplished by moving the whole camera assembly with respect to the phosphor plane. This practice has the advantage of simpler stable construction as well as allowing optimum lens corrections for fixed conjugates. The penalty is the necessity of changing the lens to change M. Where variable M is required, perhaps for a great variety of work, the additional flexibility is worthwhile, although the changing in M requires more effort than it does with an ordinary camera (Fig. 7-4).

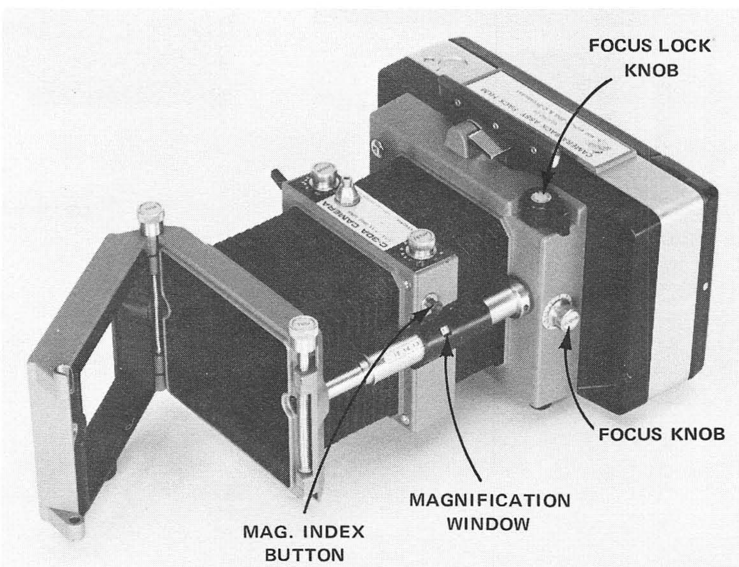


Fig. 7-4. Oscilloscope camera with variable magnification.

variable magnification

When the magnification is variable, M is usually marked on a calibrated scale and the image is focused on a focus plate. One aberration sometimes evident as M departs from 1 on either side is distortion. Graticule lines appear to pincushion or barrel, depending on M being greater or less than 1. These distortions detract from the esthetics of the picture but the resulting inaccuracies are usually less than those contributed by the oscilloscope.

focusing schemes

Scope cameras are usually focused by observing the image of the CRT trace on a diffused focus plate. If a graticule external to the CRT is used, and the main exposure is made with a wide-open lens, the graticule should be recorded by a separate refocused exposure because the phosphor plane and graticule plane will not both be in focus with widest *f*-stop. Some cameras are provided with a focusing arrangement that projects two lines that intersect at the phosphor plane; when the two lines are completely merged, the camera is in focus.

7.4. MOUNTING AND VIEWING ARRANGEMENTS

Picture-taking procedure with the simplest scope camera arrangement, such as the TEKTRONIX C-5 (Fig. 7-5), begins with a properly focused display. The camera is adjusted for aperture and time, and then held against the CRT bezel while the exposure is made. Other cameras provide for fixed mounting, where the camera may be slid onto the mount quickly. Most cameras offer hinged bezels so the camera may be swung away for display adjustments.

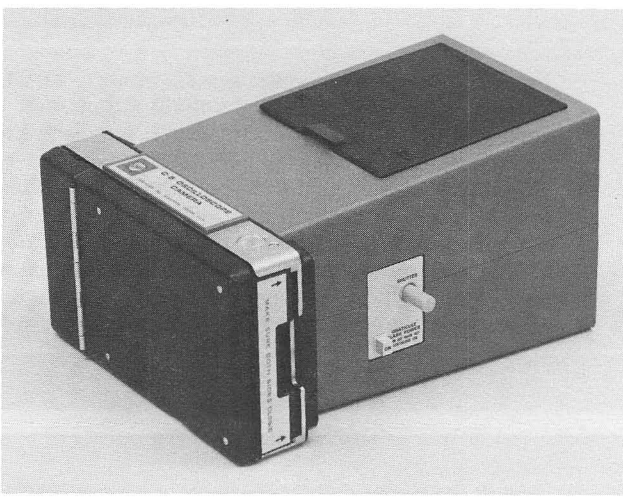


Fig. 7-5. C-5 hand-held camera.

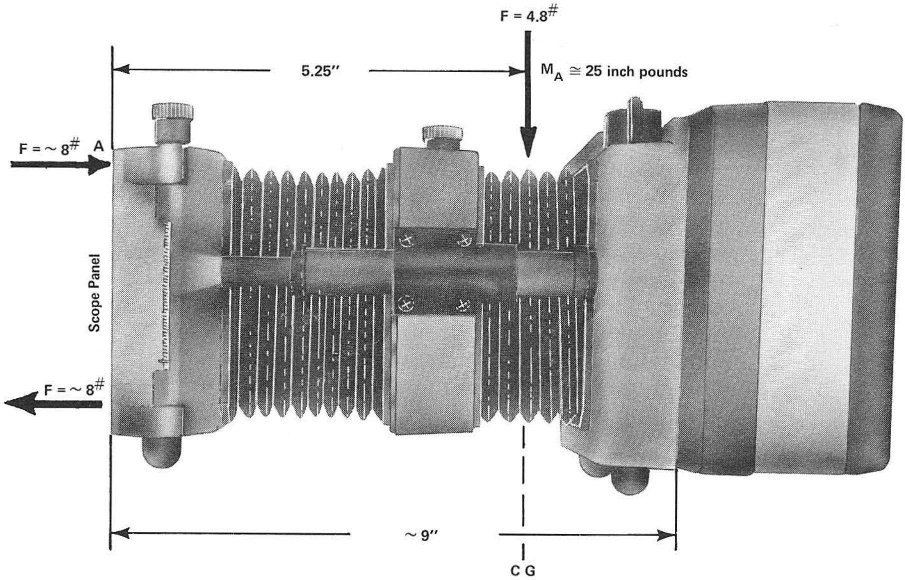


Fig. 7-6. Forces imposed on oscilloscope panel and camera mount.

Fig. 7-6 illustrates a popular camera mount; a C-30A camera is about 9 inches long and weighs about 4.8 pounds. The center of gravity is about 5.25″ from the panel, imposing a moment of about 25 inch-pounds distributed between the two upper mounting bolts. The mount unit must still support the camera when it is swung out for scope adjustments. If any work is to be done with the shutter open for prolonged intervals, the junction must be light-tight to avoid unintentional fogging. Most manufacturers provide adapters to accommodate other manufacturers' equipment, but it is best to investigate equipment compatibility before purchase.

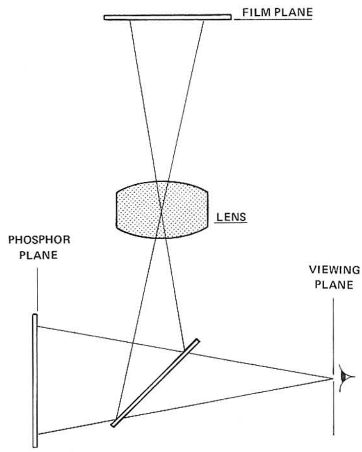


Fig. 7-7. Simultaneous viewing and imaging used in early oscilloscope cameras.

Any fixed-mount arrangement presents a design problem in providing a strong and stable mounting, while permitting complete visibility and access to the scope controls. As scope panels become smaller, the design becomes more difficult. A desirable feature, and necessary for some kinds of work, is provision for observing the display during exposure. There is no way of providing a *normal*, head-on view without adding to the complexity and cost of the camera. Some cameras provide a viewing port at an angle to the camera axis. This is fairly simple to do but provides only oblique viewing and appreciable parallax with external graticules. Normal viewing can be done only with a mirror arrangement because both the film and the viewed image are on the axis and in the same plane. The plan most convenient mechanically uses the reflected image for the film and the direct image for the viewer, Fig. 7-7. The image on the film in this case will be *reverted* left to right; sometimes the CRT horizontal deflection connections are reversed to correct the picture orientation. If the other option is used, that is, with the film optical path direct, the viewed image would be *inverted* and in an awkward position to view. The best solution here is demonstrated by the TEKTRONIX C-12, which provides another mirror that again inverts the image and presents it in a more convenient location for the viewer, Fig. 7-8.

viewing port

mirrors

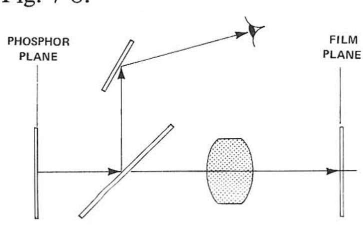


Fig. 7-8. Two mirrors preserve orientation of viewed trace.

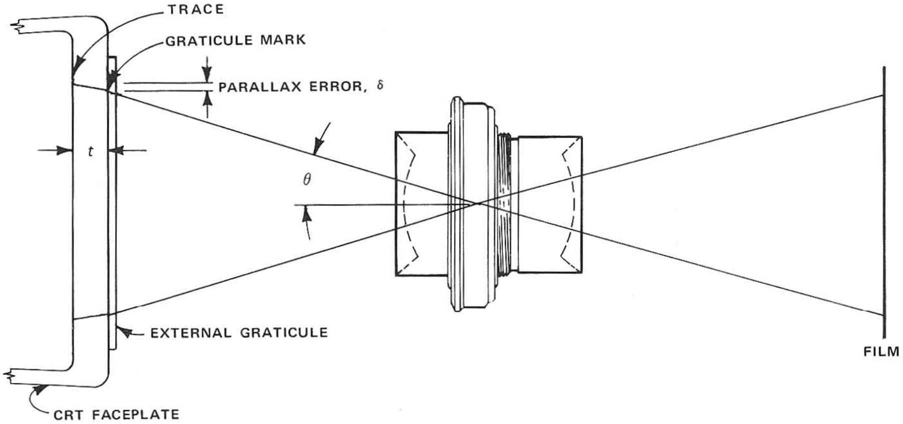


Fig. 7-9. Incorrect image calibration resulting from parallax.

depth-of-field

internal graticule

projected graticule

Another problem is that of recording both trace and external graticule markings in focus with the lens wide open, where the depth of field is less than the thickness of the CRT face. Also, parallax errors result from the displacement $\delta = nt \tan \theta$, where n = index of the glass, t = faceplate thickness, and θ = half field angle (Fig. 7-9). Current practice is to establish a graticule on the same surface with the phosphor inside the CRT. The graticule is deposited on the glass surface before the phosphor is applied. The lines are illuminated by distributing light through the edges of the glass faceplate. In general this is the most effective means of providing a graticule. A few applications require flexibility to change graticule scales and external graticules must be used. For photography in this case a good choice is a beam-splitting system which projects an illuminated graticule on the film by reflection from a beam-splitting mirror placed 45° to the lens axis (Fig. 7-10).

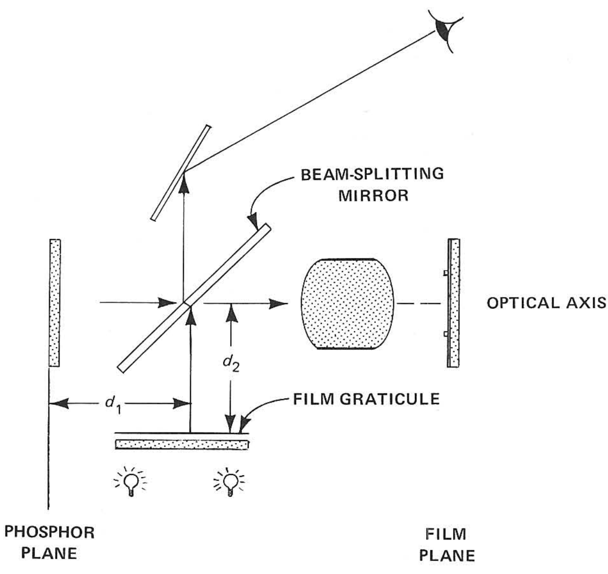


Fig. 7-10. Scheme for furnishing arbitrary graticule formats without parallax problems.

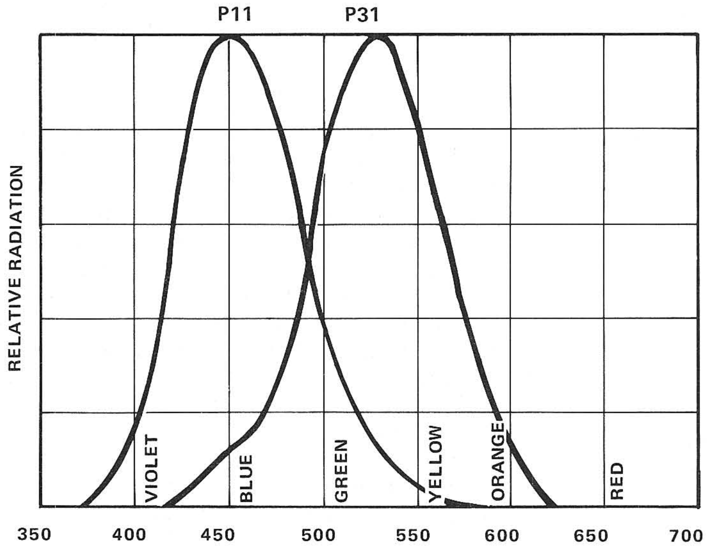


Fig. 7-11. Spectral radiation of P11 compared with that of P31.

7.5. LOSSES AND DISTORTION*

magnification affects aperture

cos^4 loss

Scope cameras are used at magnifications close to 1; that is, M is usually between 0.2 and 1. Since the effective f-number increases by a factor of $M + 1$, the aperture is always effectively smaller than that indicated on the lens assembly. For example, a camera setup for a 1:5 object-to-image ratio, $M = 0.2$, would provide 2.8 times as much exposure as a camera setup for 1:1, or $M = 1$ (exposure varies as the square of the f-number). Part of the loss is the inevitable $\cos^4 \theta$ loss discussed in Chapter 4 that cannot be changed except by changing conjugates.

vignetting

lens coating

Total light falloff will be greater than indicated because of lens vignetting, which does depend on lens design (Chapter 4). Overall losses will depend on optical factors discussed in Chapter 4 such as number of elements, number of reflecting surfaces and the lens coating used. The fastest oscilloscope camera lenses are usually coated to respond to the P11 phosphor peak at about 450 nanometers. The slower lenses may be coated to respond closer to P31 at about 540 nm (Fig. 7-11).

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*Ref: 3. Bird

barrel or pincushion distortion

The large field angles resulting from a compact camera design (short working distance) result in distortion at magnifications different from the design conjugates. Although the resulting inaccuracy is seldom serious, graticule lines will emphasize the distortion, and the result may not be acceptable (Fig. 7-12).

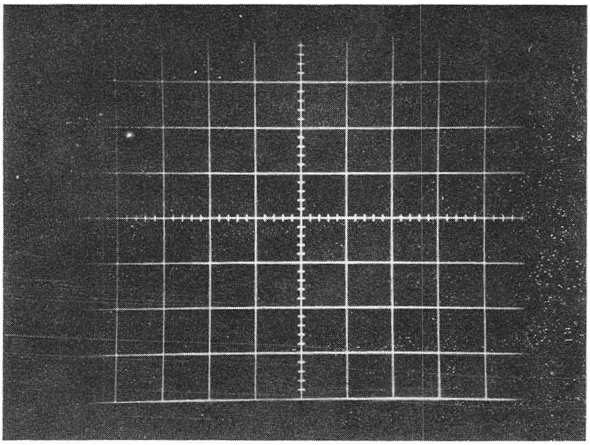

Fig. 7-12. Example of pincushion distortion.

7.6. FILM FOGGING*

development centers

When a system is working at the extremes of its energy-transfer capability, another useful technique to provide additional writing speed is the practice of film fogging. It was noted in Chapter 3 that in the emulsion under exposure the silver-ion and electron combination is unstable until another ion and electron appear at the site to form a molecule, or at least a protomolecule of free silver. This molecule becomes a development center, and a few more molecules congregating at this center establish a *latent image*; that is, the seed for the resulting image. When the exposure does not provide enough energy to establish development centers, the single ion-electron combinations disappear; they need company to survive.

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*Ref: 3. Bird
13. Hamilton

A method of providing the additional ions at the development centers would be to expose the film deliberately and uniformly over the surface by a measured amount of energy. The technique is called *fogging*. The deliberate fogging would provide incipient centers distributed throughout the film and, when the intended exposure is made, many more development centers would occur than without the fogging.

fogging

The theory has been supported empirically, first on occasions when outdated film provided writing speed much faster than expected because it had become prefogged, and subsequently by experiment in which film was deliberately prefogged or postfogged. While the theory implies that the film should be fogged before exposing the trace, results indicate that writing speed increases regardless of the exposure sequence. Results of the work described in Ref. 3 indicate that optimum writing speed results from exposing the trace first, and then fogging with low luminance for a much longer time – more than 60 seconds, at a power density that provides a fog equivalent to $D = 0.3$. General practice at this time appears to remain indifferent about exposure sequence and time interval of fog exposure, and implies that simultaneous exposure of trace and fog source is optimally effective.

fogging schemes

The greatest difficulty with these techniques is that of providing a means of consistent fogging. A measured amount of energy can be delivered to the CRT phosphor by a number of techniques – some cameras have a built-in facility for this – but as a result of off-axis light loss, the fog is not always effective at the beginning or end of the trace where it is often needed, Fig. 7-13. A better method is to fog directly by arranging to have the light diffused directly on the film. Some arrangements have been made using a circular flash tube on the film side of the lens, mounted outside the image area, around the lens barrel. The job is difficult because there isn't much room for the lamp and a diffusing plate. Fig. 7-14 illustrates a commercial film-fogging device with control for calibrated fog density. The film is illuminated directly from the source, without going through the lens.

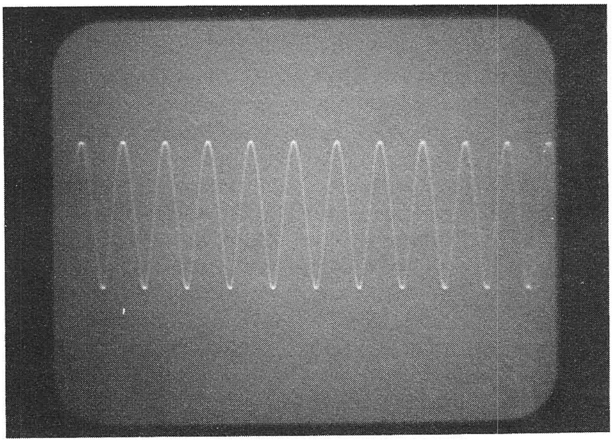


Fig. 7-13. Through-the-lens fogging results in less contrast at the ends of the trace, where it is more often needed, than in the center.

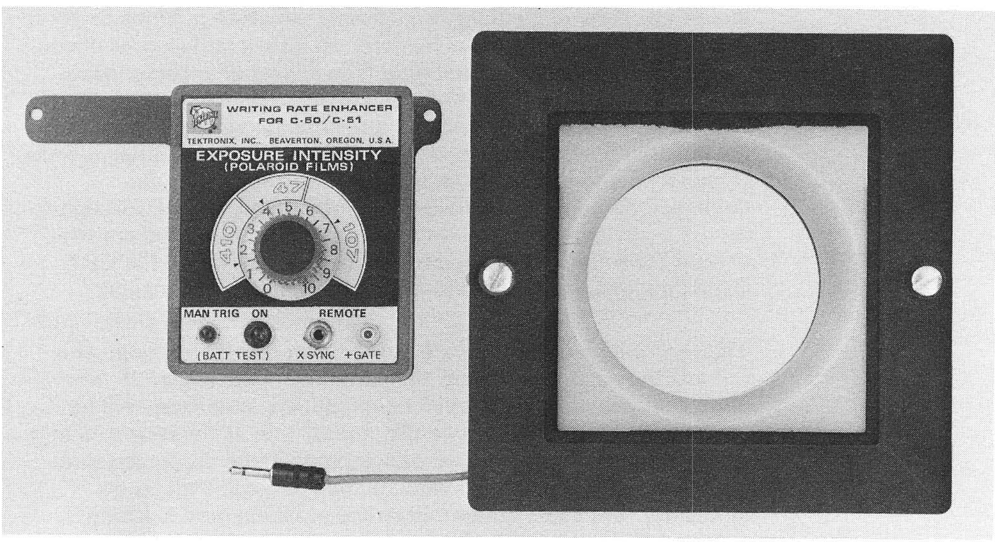


Fig. 7-14. WRITING SPEED ENHANCER by Tektronix, Inc. The plastic diffuser is mounted on the film side of the lens. The fog exposure is controlled by an electronic timer.

7.7. CONTROLS

shutters

A cable release is often used to operate the shutter on the least sophisticated systems but provision can always be made for an electromagnetically operated shutter. If an externally mounted device is used, the power applied or the energy delivered should be adjusted to assure reliable operation, but without damaging the shutter mechanism. One of the advantages of the electric control is that of operating from a remote point, also operating a number of cameras simultaneously or in planned sequence. Note that all commercial "electronic" shutters are magnetically operated; the magnetic field from the leads may introduce unwanted transients or trigger signals into the system unless proper precautions are taken.

open-shutter cautions

Most remotely controlled situations require "shutter-open" operation. The shutter is opened before the event and closed after the event. The open-shutter interval may range from one second to hours, depending on the nature of the event. During the open-shutter interval, two hazards lurk: Spurious fields are all about, trying to trigger the scope before or after the main event. At the same time, light or similar film-exposing radiation is trying to get to the film. Trigger-lockout-circuitry on most oscilloscopes insures that the sweep will be started only by a trigger of predetermined shape and amplitude, and will not be triggered again unless reset. The extent of protection needed against stray light will depend on the sensitivity of the film and the length of time the shutter is open (Chapters 5 and 6). With the sensitive films in general use, unintentional fogging occurs from ambient light leaking through to the CRT envelope, which acts as a light-pipe. Undesired emission of light from the cathode, emissions from metal inside the CRT attracting ions, and even corona discharge may cause fogging.

time

bulb

The choice of a *time* or a *bulb* position on the shutter control is not arbitrary but depends on the particular application. If *time* is used, two complete pulse cycles are required, also there will be uncertainty about which state the shutter is in at the start of a new cycle; there are programs and indicators to avoid the uncertainty but they require more hardware. If *bulb* is used, there is no ambiguity, but some kind of electrical or mechanical latching is required during the exposure period.

Aperture stops are usually marked in steps of one stop; there is no need of closer adjustment on oscilloscope cameras. Until recently the same iris and shutter arrangements used for ordinary cameras (Fig. 6-5) were supplied to oscilloscope cameras. Shutter-timing mechanisms are usually the gear-and-pallet arrangement used in most fixed-lens cameras. There is no need for speeds faster than 1/100 second, but *1 second*, *bulb* and *time* positions are usually necessary. Only reasonable accuracy of shutter speeds is necessary; other factors in the exposure equation are less predictable.

7.8. ELECTRONIC CONTROLS

shutter timing

Shutter timing and operation can be controlled more effectively electronically where the work warrants additional expense. Shutters are now made specifically for oscilloscope cameras, providing predictable delay and interval quite accurately. An electromagnetic actuator, Fig. 7-15, is designed as part of the shutter and its action is determined by the external circuit as indicated in Fig. 7-16.

The solenoid is energized by a pulse of more than 120 volts, which decays through an RC network to about 20 volts holding voltage in a few milliseconds. Meanwhile, the RC timing network charges in a direction to switch off the current through the solenoid at the end of the timing interval.

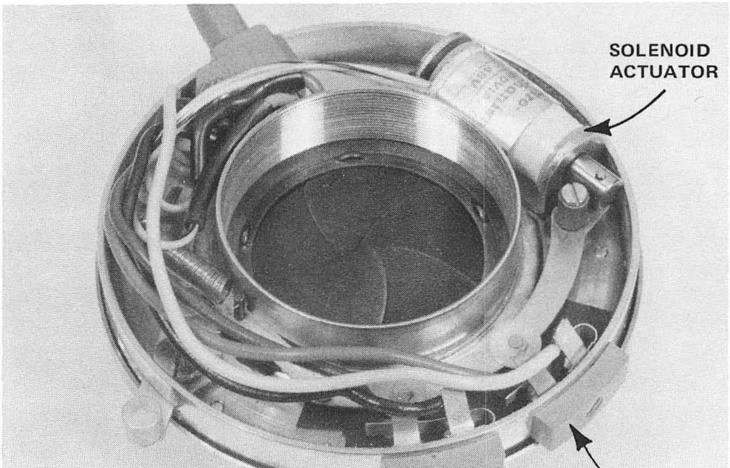


Fig. 7-15. Solenoid shutter actuator installed in shutter assembly, with microswitches.

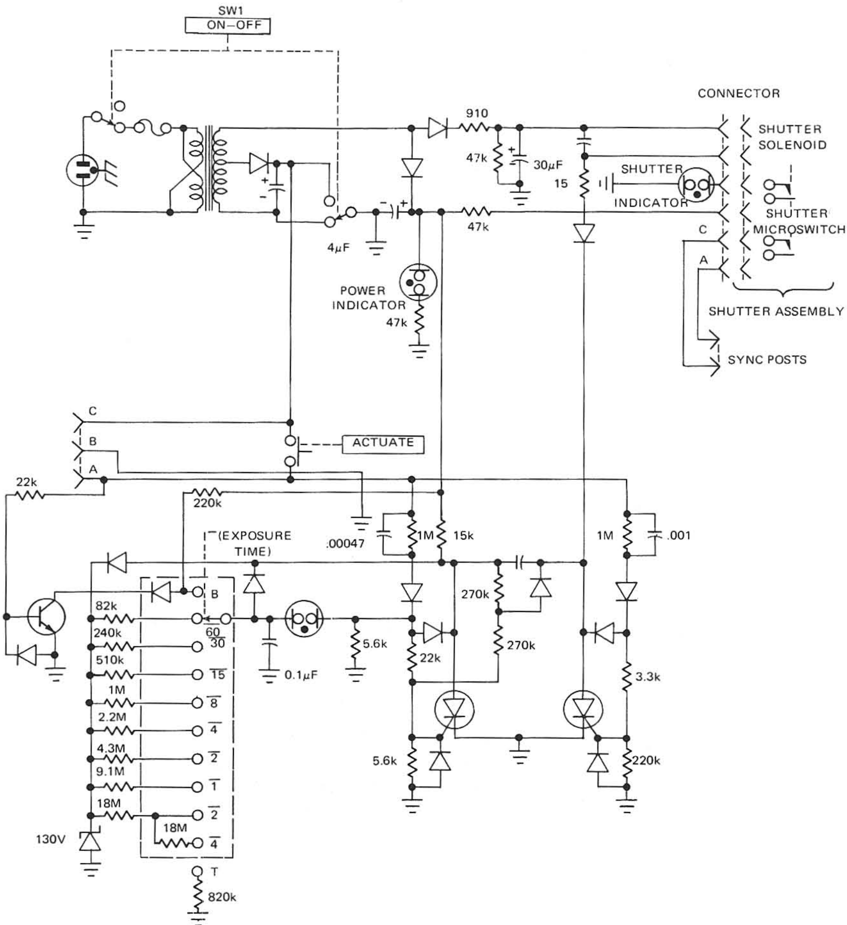


Fig. 7-16. Circuit for electronic timing and control of the electromagnetic shutter.

focusing

Fig. 7-17 shows the control panel of TEKTRONIX C-51, an example of a more sophisticated system which features a phosphor-matching trace exposure meter and a conjugate time-aperture system, as well as a fixed-distance focusing arrangement illustrated by Fig. 7-18. The lamps illuminate vertical slits, which are focused coincidentally precisely at the lens-to-object distance. At any distance other than optimum, two bars are visible; at proper focus only one thin bar is visible.

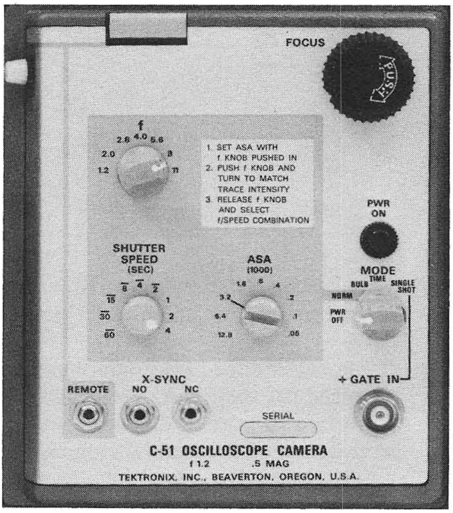


Fig. 7-17. Control panel for C-51 camera.

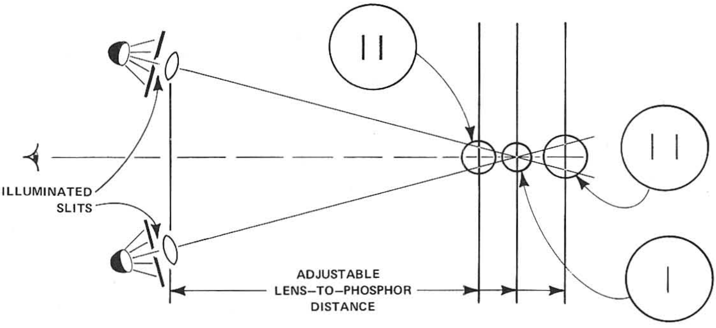


Fig. 7-18. Illustration of fixed-distance focusing system.

The visual and photographic effectiveness of some commonly used phosphors compared with P11 appear below:

Phosphor	Visual Effectiveness	Photographic Effectiveness
P1	333	20
P2	365	40
P7	234	75
P11	100	100
P31	666	50

Reliance on a visual comparison of brightness between P11 and P31 would result in as much as 13 times under- or overexposure.

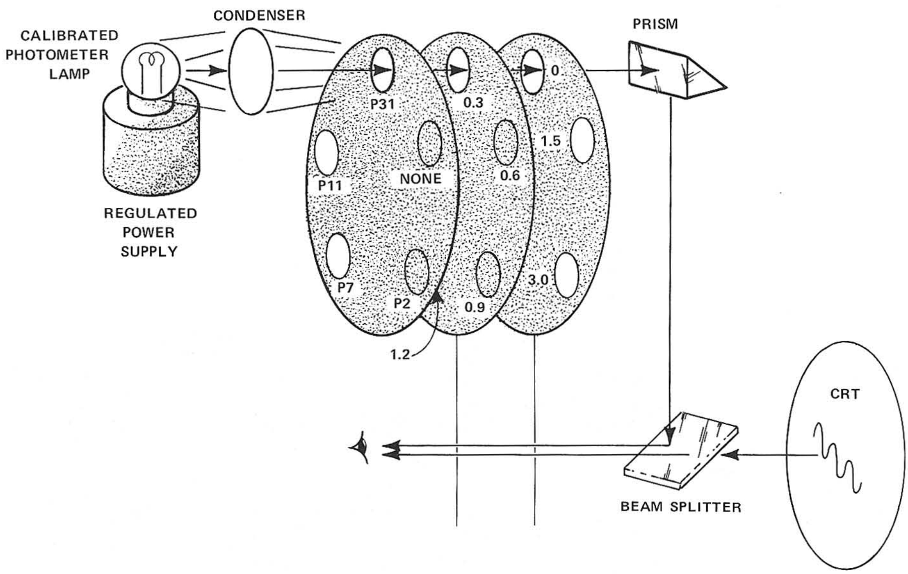
Some experienced photographers can estimate visually the exposure required for their work, but most eyes cannot compare the intensity from two sources of different wavelength. However, if the two sources are of the same wavelength, and the intensity of one can be adjusted to match the other, even an untrained eye can do well. Photometers based on this principle have been used for years. If we select a set of filters that compare closely with the luminescence of each phosphor, we can compare the trace intensity with that of a filtered reference source. If the reference source is attenuated in steps by neutral-density filters, we can measure the luminance of the trace closely enough to use in the exposure equation discussed in Chapter 6.

comparison photometer

The C-50 camera provides a comparison photometer that solves the exposure equation,

$$\frac{A^2}{T} = \frac{BS}{K}$$

as the neutral-density filters are shifted to match the trace luminance. The film speed S, the constant K and time T are fixed at the time of measurement. As filters are cut in to match the reference source with B, the aperture A is opened or closed by a linkage to the wheels carrying the neutral-density filters, as indicated in Fig. 7-19.



$$\text{DENSITY} = \text{LOG} \left(\frac{1}{\text{TRANSMISSION}}\right) = \text{LOG ATTENUATION}$$

EACH STEP = 2X ATTENUATION

$LOG_{10}\ 2 = 0.3$

POSITION		3 POSITION	TOTAL DENSITY
1	EMPTY	EMPTY	0
2	0.3	"	.3
3	0.6	"	.6
4	0.9	"	.9
5	1.2	"	1.2
6	EMPTY	1.5	1.5
7	0.3	"	1.8
8	0.6	"	2.1
9	0.9	"	2.4
10	1.2	"	2.7
11	EMPTY	3.0	3.0
12	0.3	"	3.3
13	0.6	"	3.6
14	0.9	"	3.9
15	1.2	"	4.2

Fig. 7-19. Photometer for measuring trace luminance for exposure computer.

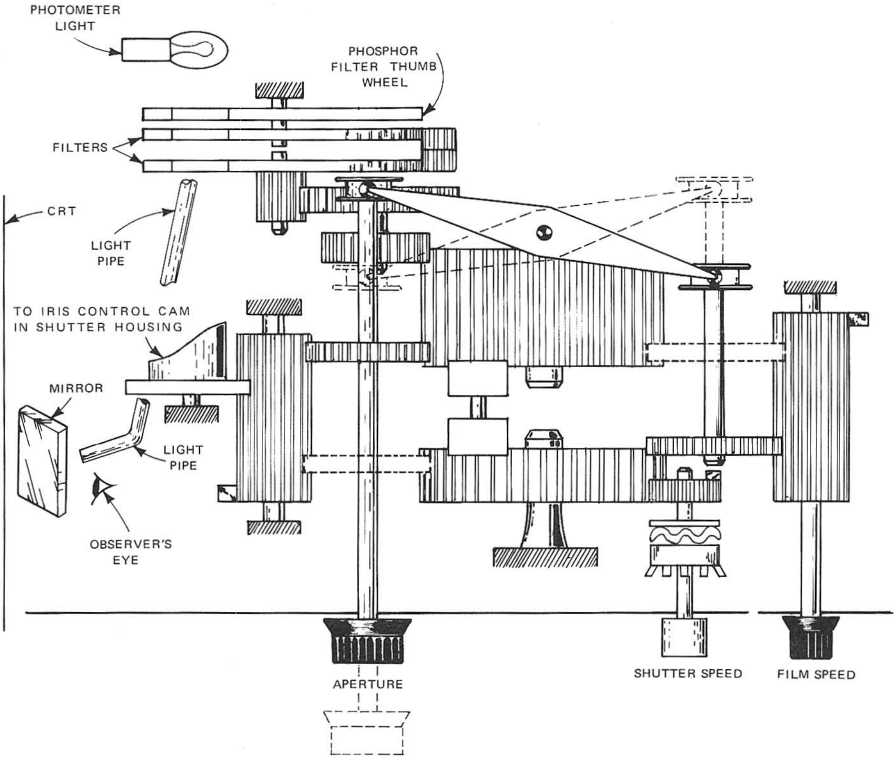


Fig. 7-20. Gearing arrangement to preserve the time-aperture conjugate $A^2 \cdot 1/t$ = a constant.

Once all the factors are entered in the equation, the exposure time may be adjusted, and the aperture will assume its conjugate value, or if the aperture is adjusted, the time will assume the proper value. These effects are accomplished by the mechanical linkage and gearing arrangement shown in Fig. 7-20. Provision is also made to operate in *bulb* and *time* positions without the photometer, as well as to operate *single sweep.*

picture identification

Some additional features are often provided for special applications. For example, picture identification is important where many exposures of a similar display are needed. Some cameras provide a serial counter that images an illuminated number on the film. Tektronix, Inc. provides a Projected Graticule described earlier that can image handwritten notes on the picture. A new oscilloscope feature is the digital scale information displayed on the CRT face, which also appears on the picture. Even without the identification features, a simple orientation code in one corner of the graticule could avoid the annoyance of having an illustration printed upside down.

shutter mode

When the camera is operated in *time*, *bulb*, or single-shot position, an indicator is needed to show that the system is armed, and in *time* position, to show whether the shutter is closed or open.

7.9. CRITERIA

It seems obvious that a camera should be chosen to provide no more than the requirements demand; most cameras offer much more than necessary in order to be available for unanticipated projects.

The following criteria can be used to guide in selecting an oscilloscope camera. The order of the items on the list has no significance; priorities can be assigned after the requirements have been established:

1. *Maximum Writing Speed*: This criterion is very often first and may be most costly. If not first in importance, it will probably be last.

2. *Time Saving and Convenience*: Polaroid is at this time the most convenient film to use, and the most costly. Time-saving considerations are convenience of set-up, trace viewing for scope adjustment, change of magnification, stepping of film back or trace for comparisons. This criterion is referenced to the time cost of the operators involved.

3. *Use of the Record*: Where the picture itself is part of the project objective, it may be an advantage to use a negative film. Copies can be made on blueprint machines or photographically. The size and format can be varied to use one of a number of commercial films.

4. *Resolution*: Not often important for imaging the usual traces; sometimes too much concern is given to lens resolution, when the particular CRT can provide only a few lines per millimeter.

   A review of the lens aberrations discussed in Chapter 4 suggests that for repetitive traces, or all photographs of a visibly motionless waveform, and where no better than usual CRT resolution is needed, lens corrections need not be extensive.

   lens minimum criteria

   When exposure time is adequate, as it is with a motionless subject, a much smaller aperture can be used, reducing spherical aberrations and coma.

   Because the camera will be used at only one focus distance, astigmatism can be optimized by lens shape. Field curvature and distortion can be controlled by using a longer working distance. There will be no problems with chromatic aberration because only a small part of the spectrum will be used for any oscilloscope work. If a relatively large working distance can be tolerated, and usual CRT trace widths are adequate, almost any lens with the proper focal length will work on repetitive-trace photography.

5. *Environment*: Cameras are subject to different kinds of abuse, but there are conditions of operation which may affect any element in the system. Temperatures high enough to damage the camera destroy the film. Very low temperatures are hard on the moving parts, such as diaphragms, shutters and their linkages. Nuclear radiation may damage lenses. Means can be provided in most cases to protect camera and film from known hazards.

7.10. SPECIAL CAMERAS

streak camera

A number of specialized cameras are in use for particular requirements. For example, it may be necessary to record a series of relatively fast transients over a period of minutes. The galvanometer oscillograph can spread the time coordinate out to many feet, but response is limited to the order of 5 kilohertz. By using a *streak* camera, a camera without a periodic shutter, in which the film moves at a constant rate, the horizontal coordinate is extended as far as the film will accommodate; say 100 feet. The oscilloscope time base is disabled before the camera is started.

split-image cameras

Another interesting requirement is that of providing simultaneous pictures of an operating mechanism and an oscillogram displaying a parameter such as strain or deflection. The camera has separate optical trains, one focused on the mechanism and one on a camera-synchronized scope display; the images are formed side by side on individual frames of 35-millimeter film.

CRT scanning

dry-silver medium

A system of special interest is TEKTRONIX 4601 Hard Copy Unit, designed to copy the alphanumerics and graphics presented on TEKTRONIX Storage Display Units. The CRT beam in the 4601 is deflected only in the y direction. The faceplate is a narrow fiber optic strip providing a writing area approximately 20 x 0.5 cm. Signals from the 4601 cause the Storage Display Unit to scan the storage CRT, and return video (Z-axis) signals to modulate the beam of the 4601 CRT. A dry-silver sensitized paper is drawn across the CRT at the same rate the storage tube is scanned. The paper is then drawn over hot rollers; this is the development process. The great advantage of this dry process is the relative mechanical simplicity of processing, without a requirement for wet chemicals. Exposure required is several thousand times that for Polaroid 47/107.

8

SYSTEM RESPONSE

System Response can be described by two major criteria: Spatial Response and Time Response.

8.1. SPATIAL RESPONSE*

resolution

Spatial response defines information surface density in terms of bits per linear dimension (lines per millimeter, cycles per millimeter). Measurements are made by direct scaling or by averaging (Chapter 3).

trace width

For the average laboratory scope, a trace width of 0.25 mm (0.01″) at low beam current is very good; a few high-speed scopes have better. This trace width implies a resolution of less than 4 lines per millimeter. Particle size of a fairly coarse phosphor would provide 50 *l*/mm, more than ten times the trace resolution, consequently for general applications, phosphor particle size is not significant. If high-speed recording is not primary, or if a single shot is not necessary, the trace can be made much brighter and the resolution may be doubled as a result of the higher contrast. If the trace is repetitive, periodic electronic noise in both horizontal and vertical circuits (jitter and hum) may broaden the trace, and white noise may bury the signal.

lens & film

The fastest films used for trace photography provide about 25 *l*/mm, even with fast processing. A fast lens may be as poor as 10 *l*/mm at the edges. This lens and film combination would provide about 7 *l*/mm resolution of a low-contrast target; a better lens, with say 25 *l*/mm at the edges, would improve the results to about 12 *l*/mm. For most applications of oscilloscope photography, required resolution is limited by the width of the trace to around 10 lines per millimeter, not a very demanding requirement.

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*Ref: 44. Wurtz
28. Riesenfield
21. Kodak (a) (f) (g) (h)
15. IEEE

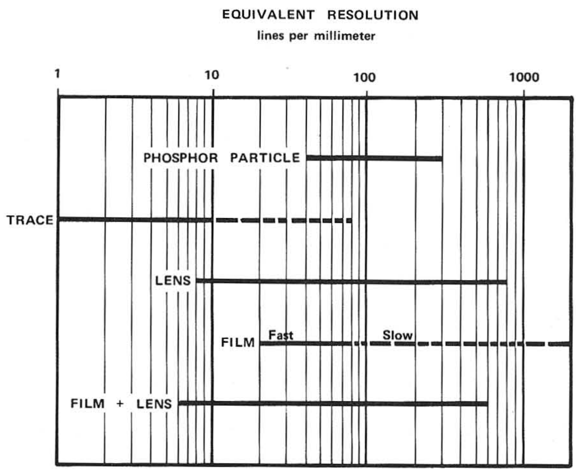

Fig. 8-1. Correlation of dimensions influencing system resolution.

LENS RESOLUTION TABLES
lines per millimeter

			CENTER RESOLUTION*							EDGE RESOLUTION* (5 cm from center)						
			f/1.4	f/2	f/2.8	f/4	f/5.6	f/8	f/16	f/1.4	f/2	f/2.8	f/4	f/5.6	f/8	f/16
1:1	WOLLENSAK	f/1.4	36	36+	36+	36+	36+	36+	36+	18	18	18	18	18	26	26
1:0.9	ELGEET	f1.9		40+	40+	40+	40+	40+	40+		28	28	28	28	28	28
1:0.9	WOLLENSAK	f/1.9		40	40+	40+	40+	40+	40+		14	14	14	20	20	28
1:0.5	ELGEET	f/1.3		72	72+	72+	72+	72+	72+		36	36	36	36	36	36
1:0.5	WOLLENSAK	f/1.9		72	72+	72+	72+	72+	72+		18	18	26	26	26	36

*Focus was somewhere between center and edge.

Table 8-1.

uniform resolution

If uniform resolution over the complete recorded image is paramount, all the technical priorities will have to be readjusted. Circuit and deflection linearity take precedence over risetime, and spot diameter takes precedence over intensity. In high-speed oscilloscopes there is always a perceptible broadening of the trace at the scan extremities. Usually, magnetic focus and deflection are necessary for very high-resolution displays, and writing speed is less.

optimizing resolution

For better resolution in the photographic record, the camera working distance may be increased, M made smaller, and the lens corrected differently. Provision can be made to use film and processing that yield higher resolution. Fig. 8-1 shows approximate ranges of resolving power of lens and film compared to resolution available from the cathode-ray tube.

Because most scope displays do not occupy a large area of the screen, it is usually possible to confine the critical-resolution portion of the trace to the center of the display where nearly all criteria are optimum.

8.2. TIME RESPONSE*

writing speed

Time response defines the information-power capability of a system. Writing-speed measurements are designed to answer the question: "What is the speed of the fastest trace the system will record?" A convenient measure of writing speed is expressed in cm/μs or in cm/ns. The writing rate of an undeflected trace traversing the screen is the inverse of the indicated sweep time per centimeter. However, there is no factor in this measure that indicates how much information will be available from the written trace. If the amplitude of the critical information is only half the width of the trace, the results may not be useful. For this reason a more critical measure is trace-widths per second. *Information Writing Speed* is defined as "a measure of the maximum number of spots of information per second that can be recorded and identified on a single trace."

information writing speed

When extremely high writing speeds are discussed, we may be reluctant to quote or specify a "writing speed" greater than the speed of light, c. While the trace itself cannot traverse the screen faster than light, it is not improper to refer to an *equivalent* writing speed faster than the speed of light, and such speeds are indeed being recorded.

equivalent writing speed

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*Ref: 21. Kodak (a) (c) (e) (h)
15. IEEE

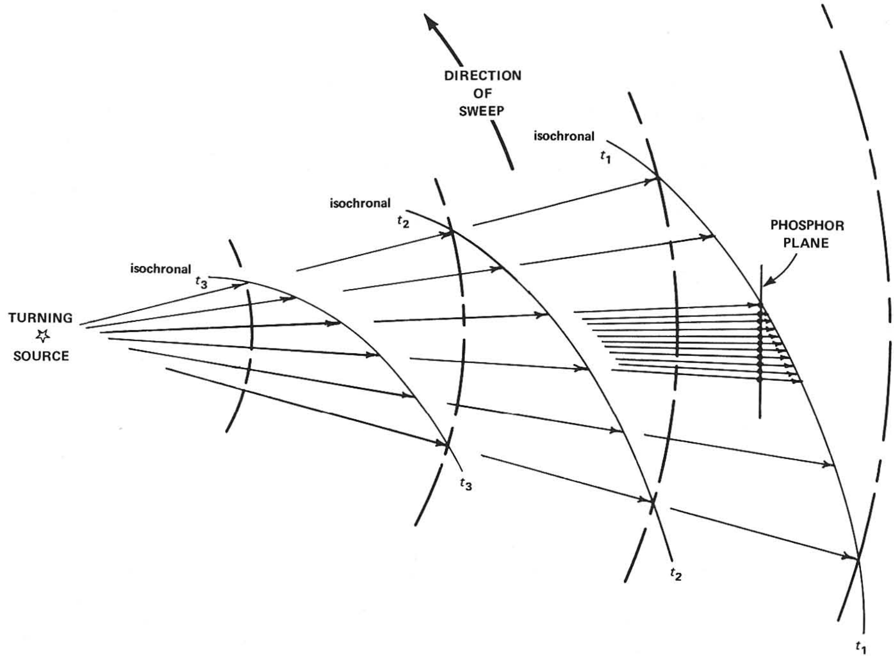

Fig. 8-2. The individual particles in the beam of a rotating beacon all move in a straight line. The sequence of events at the target occurs in an interval of time not governed by the speed of light but by the number of particles and the angular velocity of the source.

If we think of the beam as a rotating source radiating a narrow beam or *pencil* of light, similar to an aircraft beacon visible for many miles, it is apparent that the peripheral velocity of the beam will, at a certain distance, exceed the speed of light. Because the light cannot travel faster than c, each photon will arrive at the periphery later than the projection of the beam (Fig. 8-2). In the CRT it is possible for the projection of the beam of electrons to traverse the faceplate faster than c, but the electrons arrive later than the projection of the beam. In addition, the phosphor buildup time is longer than traverse time of a fast trace, so the actual illumination of the trace is delayed still more. Even though the electrons are delayed, and reach the phosphor after the projection of the beam has passed, they are all delayed by the same increment of time; the time interval between the excitation of the first phosphor particle on one end and the last phosphor particle at the other end will be the same as the traverse time of the projected beam. Actually the concept is not invalidated by the limit c, because the apparently moving trace is a succession of events, physically positioned to display a line.

8.3. WRITING RATE MEASUREMENTS*

If a trace of constant beam density is measured and the horizontal component converted to time according to the sweep-time setting, the ratio of distance to time is writing rate (Fig. 8-3). A trace that can be most accurately measured should be long enough to minimize physical measurement errors, and straight enough to measure easily. One rise of a sawtooth or a trace of a fast transient will do, but a succession of exposures must be made to determine where the density difference falls below the specification. The usual method is to generate a damped sinewave of known frequency, Fig. 8-4. The amplitude of the excursions will decay exponentially; by adjusting the Q of the generating circuit, that amplitude can be made to decay over a range adequate to select a straight part of the cycle whose density difference is 0.1 (or that specified) over background density.

damped sinewave

The writing rate, or maximum writing speed = $A\pi f$, in linear units per unit time, where A is the peak-to-peak amplitude of the half cycle of specified density measured physically in the units to be expressed and f is the frequency of the damped sinewave. Time is often expressed in microseconds or nanoseconds to avoid large numbers. Fig. 8-5 is a chart for system writing rate required for recording specific risetimes.

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*Ref: Kodak (c)

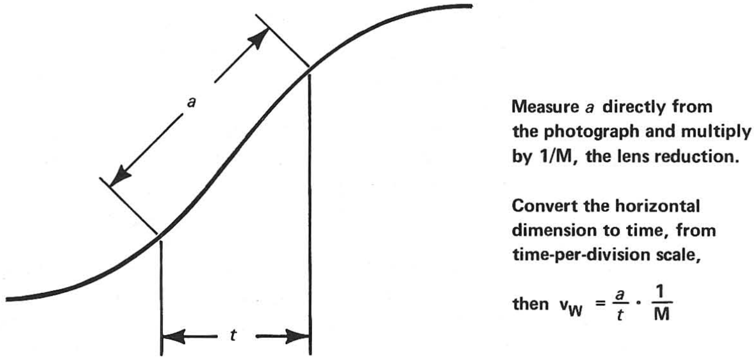

Fig. 8-3. Calculating writing rate directly from the photograph.

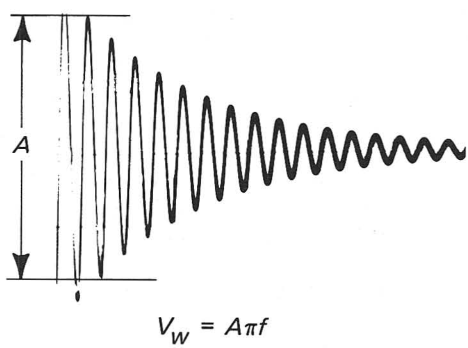

Fig. 8-4. A damped sinewave provides a means of measuring writing rate without making a series of exposures.

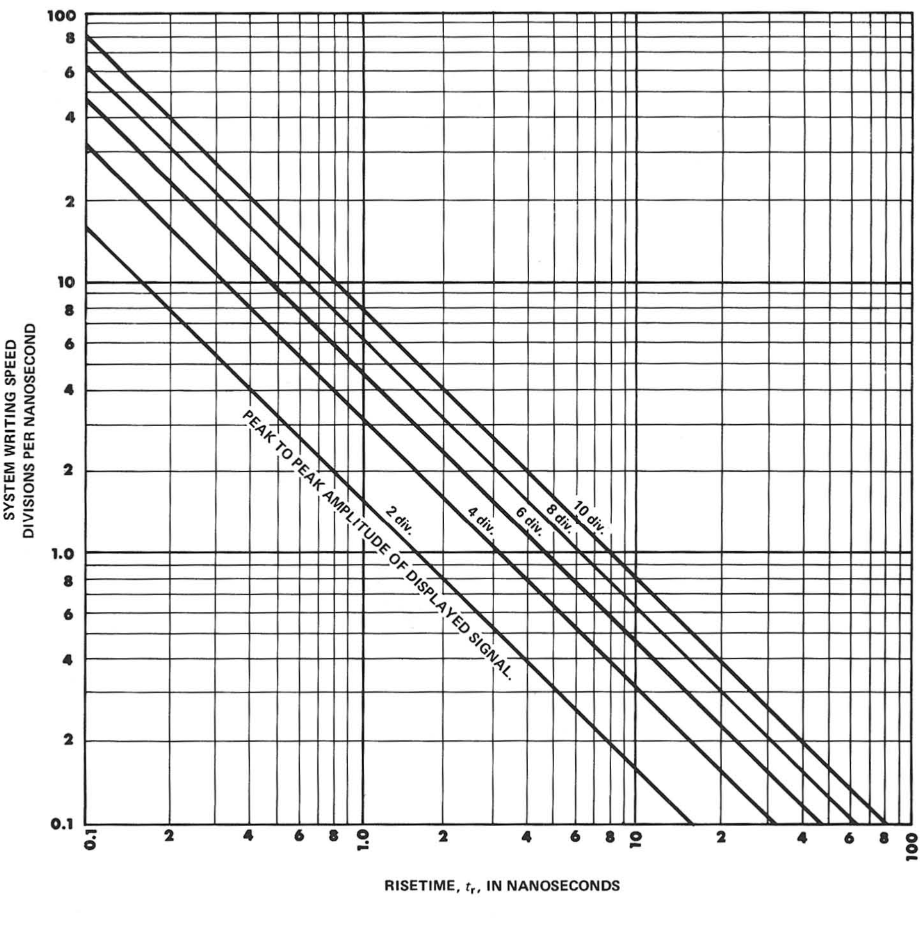

Fig. 8-5. Chart for determining writing rate required to photograph a trace.

overscanned transients

Another method of finding maximum writing rate is by windowing a transient that has been driven vertically off scale. If the vertical amplifier has enough power, the attenuation can be reduced to increase the deflection and overscan the CRT, increasing the trace speed accordingly. When the 10-to-90% risetime of the generator is measured, and the pulse displayed at maximum sweep speed, the vertical amplitude of the display can be increased ten times and the trace speed will be increased ten times (Fig. 8-6).

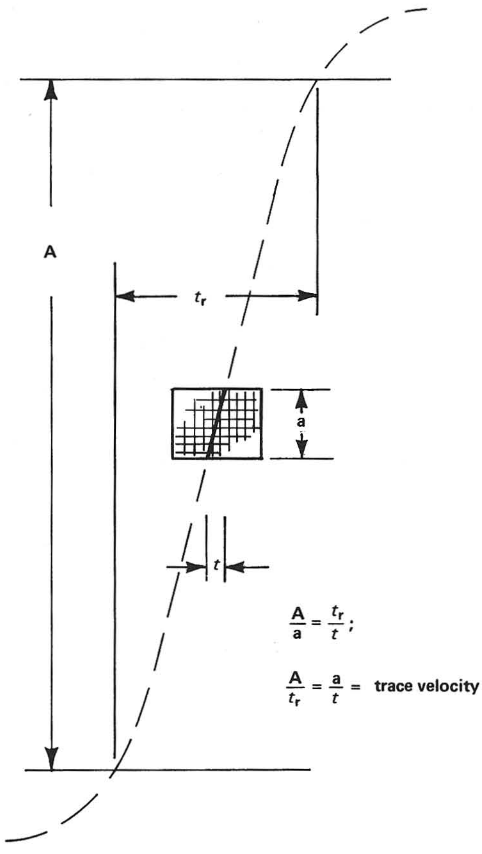

Fig. 8-6. Measuring writing rate by windowing.

conditions

All measurements for writing rate must specify conditions, including the definition of a readable trace. A trace is usually considered readable if the density difference between trace and background is 0.1. This difference can be detected visually and can be expected to reproduce adequately for publication.

8.4. POWER TRANSFER EQUATIONS*

radiant emittance at faceplate

The equation for radiant emittance at the faceplate, power per unit area (Chapter 5) is:

$$W = \frac{VI\phi}{dl}\text{, watts per unit area} \qquad \text{(Eq 8-1)}$$

and these factors can be measured closely:

V = volts from cathode to post-deflection anode,
I = beam current for duration of the trace, amperes,
d = trace width, measured by shrinking raster, } same units
l = length of trace, with no discontinuity. }

The factor ϕ includes factors calculated or measured for the particular CRT, operating under particular conditions. For the same phosphor, ϕ will vary appreciably under different anode voltages and beam currents; it will vary somewhat with CRT's of different manufacturer, depending on the methods and materials used to deposit the phosphor on the faceplate. For different phosphors on the same type CRT there will be great differences due to different quantum efficiencies of the phosphors. The short-wavelength phosphors are much more efficient. The phosphor-conversion factor will be constant only for a specified phosphor, CRT, and operating conditions.

units

The dimensional units in the equation can be arbitrary; trace widths are often measured in *mils*, that is thousandths of an inch. If we intend to use metric terms for film sensitivity, it may be easier to change units at this point. The other units are volts and amperes; powers of ten are easier to keep straight than terms for multiple and sub-units.

Without the factor ϕ, we have only an expression for power per unit area delivered to the faceplate. After applying ϕ, we have radiant power density that can be measured in watts per square centimeter.

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*Ref: 2. Beiser
3. Bird
7. Derr
41. Tyler

Illuminance at the film plane is:

illuminance at film plane

$$E_e = \frac{P}{d \cdot l} \frac{\phi T \cos^4 \theta}{4A^2 (M+1)^2} \text{ watts per square centimeter} \qquad \text{(Eq 8-2)}$$

T = lens transmission factor,

θ = angle at second principal plane, between axis and ray leaving lens,

A = *f*-number,

M = magnification.

T is the transmission factor of the lens at maximum aperture; it includes accumulated losses in glass transmission and reflections over the spectrum radiated by the phosphor. The $\cos^4 \theta$ factor is not usually shown when the expression implies on-axis illuminance. We include it because the field angle in scope cameras is wider than that in the usual camera, and loss of light at the edge of the pictures is often evident. This loss is not due to poor lens design, but rather to geometrical consequences as noted in Chapter 4. An off-axis factor not included results from vignetting, discussed in Chapter 4; it also depends on θ but is peculiar to the particular lens design. Vignetting contributes materially to loss of light at the edges of the film plane. The significance of the other factors, the *f*-number, A, and magnification M should be evident.

Exposure E_x, a measure of energy density, is available immediately from Equation 8-2, as the product of power density and period of exposure: E_x = watt-seconds per square centimeter. A more convenient quantity is $E_x = 10^{-7}\, Ht$, ergs per square centimeter; this quantity is more often applied to data on scientific films. Exposure values for popular films are expressed in meter-candle-seconds; if all the phosphor energy were radiated at 555 nanometers, then $E_x = 1.47 \cdot 10^{-7}\, Ht$, meter-candle-seconds.

8.5. SPECIFICATION OF WRITING RATE*

Writing rate characteristics of a system should include:

1. Lens speed and magnification and manufacturer's identification.
2. Film manufacturer's type number.
3. Film processing conditions.

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*Ref: 15. IEEE

4. Density difference between trace and background.
5. Units of measurement.
6. Definition of enhancement procedures (fogging).
7. Oscilloscope type and phosphor, with any modification significant to writing rate such increased final anode voltage.

The lens speed (*f*-number) will be the effective aperture at the specified image-to-object ratio, *M*. Lens transmittance *T* will be influenced by the response of the lens coating to the spectrum of the phosphor used.

8.6. FILM CHARACTERISTICS*

speed ratings

We have been in the habit of referring to ASA film speed. As pointed out in Chapter 3, there are different film speed rating systems for different photographic applications. The ASA speed system was designed for pictorial photography, using light power units rather than radiation units, relating judiciously to tone values, and to density differences of more than 1.0. The ASA system is not at all suitable for fast CRT recording, where exposures fall at the toe of the characteristic curve and the density need not be more than 0.1 above base density to be useful. It is also more appropriate to use *ergs per unit area* than *meter candle seconds* for exposure units, because the integration procedures used in relating film spectral response to phosphor spectral distribution can avoid the additional steps of watts-to-lumens and lumens-to-watts. An example of the possible gains or losses resulting from phosphor-film spectral relationship is shown in Fig. 8-7.

reciprocity failure

The film characteristic of reciprocity failure was discussed in Chapter 3; curves are available for most films, but none of the curves extend into the nanosecond region, where fast traces are recorded. One of the fastest films available, Kodak 2485, exhibits only a small departure from reciprocity at 10^{-6} seconds, but no data are available for shorter times. All recent experience indicates that reciprocity holds fairly well into the nanosecond region. By increasing the illuminance at the film plane by a measured amount, the exposure time can be reduced proportionately, at least within 100%. As exposure time becomes shorter, CRT exposure measurements become more difficult and less accurate.

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*Ref: 3. Bird
7. Derr
13. Hamilton
33. Shoffer and Dutton

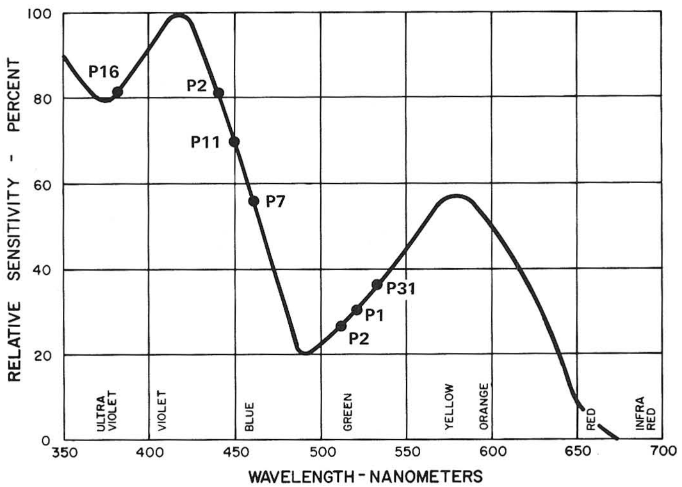


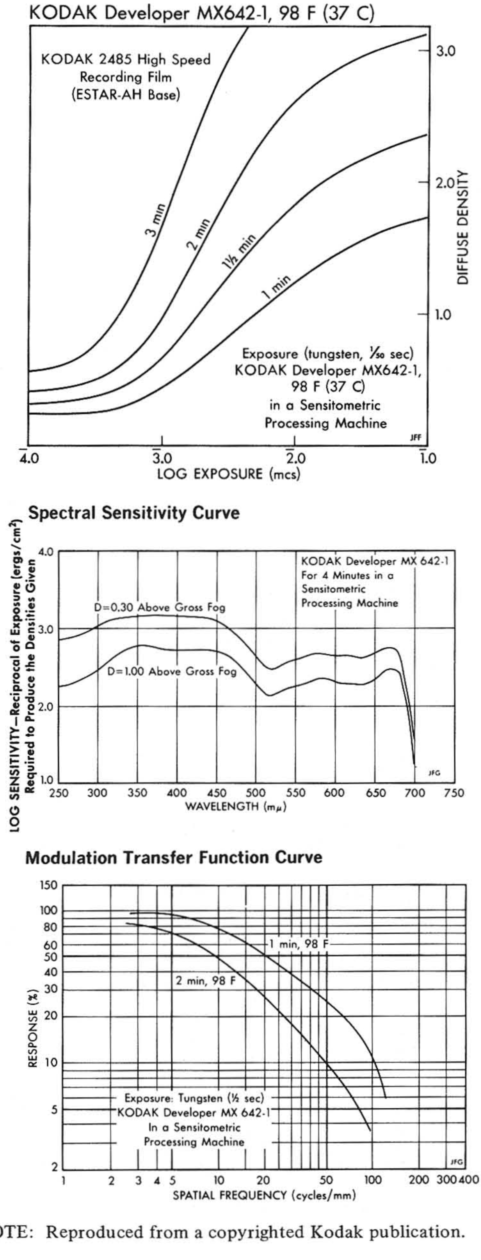
Fig. 8-7. Radiant sensitivity of Polaroid Type 410 film.

development

Where ordinary film processes are used for fast-transient records, greatly increased photographic speed can be provided by adjusting the processing. The characteristic curves for special films show that gamma, the ratio of density to log exposure, increases with time and temperature. Since very few scope operations show grey-scale information, films can be processed for maximum gamma, which increases sensitivity *and* fog. The toe of the curve then extends further toward the low-light level region but also rests on a higher gross fog density. Some comparative development figures are noted in Fig. 8-8.

At this time Polaroid's fastest film, Type 410, is available only in roll form and cannot be used in the processing back made for the convenient Type 107 Polaroid film.

Fig. 8-9 gives the response of Polaroid Type 47 with notes indicating the latitude in terms of reflection density. The response will be appreciably faster with P11 phosphors, and poorer for P31. The speed can sometimes be increased by using a slightly shorter development time.



NOTE: Reproduced from a copyrighted Kodak publication.

Fig. 8-8. Processing effects of Kodak 2485.

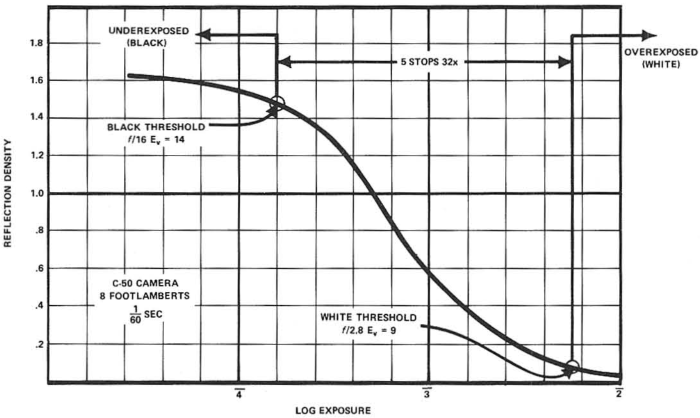


Fig. 8-9. Characteristics of Polaroid Type 47.

fogging

Latensification, or enhancement of the undeveloped image, by deliberately fogging the film was discussed in Chapters 3 and 7. The need for increased writing rate has accentuated efforts to provide dependable, measured fogging where the gain is significant. It should be recognized as a measure used only for additional speed and that some deterioration of resolution should be expected.

Evidence of increase in writing speed by several times is indicated by Fig. 8-10.

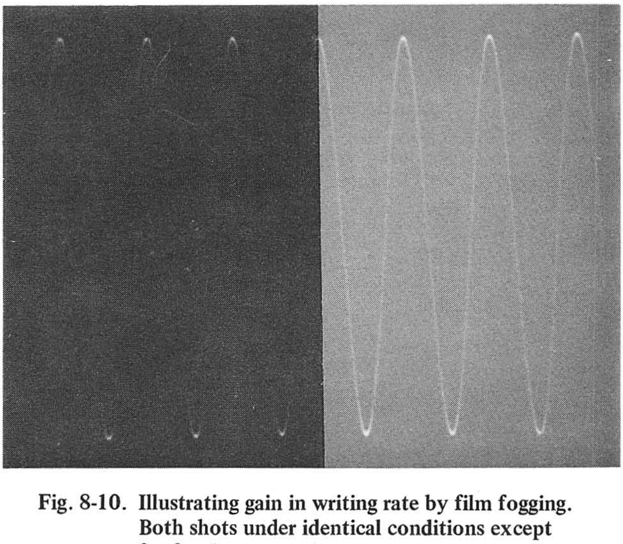


Fig. 8-10. Illustrating gain in writing rate by film fogging. Both shots under identical conditions except for fogging.

8.7. NOISE

Noise exists in the signal being measured, and shows up in the vertical system as electrical noise. Other noise is contributed by the vertical and horizontal circuitry. Except for extremes of bandwidth or sensitivity, electrical noise is adequately suppressed by good circuit design, and the photographic elements of the system should have no effect on electrical noise. Where a repetitive trace is displayed at high repetition rates, a trigger signal that changes time-position with respect to the signal of interest, will introduce jitter, or time instability, resulting in a broad or fuzzy vertical component in the trace. Under some conditions, the trigger can also introduce vertical jitter. Sometimes it is possible to reduce these effects by reducing the number of times the display is exposed (repetition rate). Noise originating in the signal, such as white noise, depends on bandwidth and time; there are techniques for retrieving a signal buried in noise described in texts and journals.

electrical noise

These electrical noise elements result in linear distortions of the recorded display, but photographic noise results in density distortions of the record. Photographic noise may begin at the CRT gun in any manner that causes a spurious emission of electrons or light or even ions. Phosphor discontinuities or contamination, scintillation, light leaks through the glass, excitation of the phosphor by means other than the electron beam, all these are photographic noise, and contribute to the background density of the film which affects the photographic signal-to-noise ratio that in turn limits the information capacity of the system. Some of this noise is lens loss, some is included in the emulsion, and some results from the particular film process used.

photographic noise

8.8. NONCONVENTIONAL SYSTEMS*

If Equation 8-1 is divided by Equation 8-2, the result is the energy-loss factor introduced by the phosphor and the optical elements. In a well-designed system for fast recording, the loss factor cannot be reduced to much less than 200 times. For this reason efforts have been made to record CRT displays without using normal photographic means.

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*Ref: 39. Tarnowski
24. Mees and James

fiber optics

The use of a fiber-optics faceplate makes it possible to apply the film directly to the faceplate, and avoid the ordinary optics losses. The CRT faceplate is a disc sawed out of a fiber-optics bundle. The disc must be strong enough to withstand atmospheric pressure, and contain enough fibers to provide needed resolution. The phosphor is applied to the inside face of the disc before it is fabricated into the CRT envelope. In use, the radiation from the phosphor proceeds only (ideally) through the fibers to the outside surface. The energy efficiency of this system provides more than ten times the light available to the film as that of a lens system. The most serious limitation appears to be the mechanical problems of applying the film in contact with the faceplate, exposing the film, then removing it to the processing position without inadvertent exposure. At this time not many fiber-optics faceplates are used for recording fast traces.

electron beam recording

Another means of avoiding the high optical losses as well as some of the phosphor efficiency losses is that of writing directly on the film with the electron beams. The response of sensitized film to the electron beam is discussed in Chapter X of Mees and James. Not only is the power efficiency of the system improved greater than an order of magnitude, but greater resolving power is possible. It is interesting to note that at the beginning of the century the first oscillograms from CRT's were made by this technique. The limitation of the system is the obvious problem of containing the film within the CRT. To load and unload, the CRT must be unsealed, then resealed and pumped down. The procedure must take place in a meticulously clean environment. Oxide-coated cathodes cannot be used because they cannot withstand the unsealing cycle. The film must be thoroughly outgassed before the CRT is adjusted.

8.9. SUMMARY

High writing speed requires optimization of all pertinent elements of the system. Below is a list of elements listed under four categories of influence. The skill (and acute eyesight) of the operator can make a difference of several times in writing rate.

Controlled by design and manufacture

- Final CRT voltage
- Spot size
- Beam current density
- Edge defocus
- Deflection plate intercept
- Unblanking pulse shape
- Phosphor and aluminum backing
- Lens transmission
- Light fall-off
- Magnification
- Effective aperture
- Graticule or face-protector loss

Controlled by system assembler

- Selection of scope design
- Magnification
- Film and process options

Controlled to design objectives by calibration

- Regulation
- Trigger circuits
- Sweep holdoff and lockout
- Unblanking
- CRT operating voltages

Controlled by operator

- CRT focus
- CRT astigmatism
- CRT beam intensity
- External graticule
- Light filter
- Magnification (with some cameras)
- Lens aperture
- Camera focus
- Film type
- Film processing
- Film fogging

BIBLIOGRAPHY

The references are provided for readers who want more detailed treatment of the particular subject and for those who want to study it more seriously.

The texts listed were chosen because they were available. There are many other useful and authoritative books on optics and photographic phenomena.

The two that are easiest to read are Cox (Ref 5) and Neblette (Ref 27); Neblette provides perhaps the best one-volume coverage of photographic technology. The books on optics fundamentals are useful to the average technician, but those on light-emitting and light-sensitive materials are difficult for those without a good background in solid-state physics and in organic chemistry. Sproul (Ref 36) may provide helpful background on luminescent and photosensitive materials.

1. ANSI, American National Standards Institute; formerly USAS
   (a) PH 2.12 Exposure Meters
   (b) PH 3.37 Lens Transmission
   (c) PH 2.25 Printing Density
   (d) PH 3.18 Shutter Synchronization
   (e) PH 2.19 Diffuse Transmission Density
   (f) PH 2.5 Speed of Negative Materials

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