Real-Time Radiography

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Manuscript date: February 26, 1981

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Real-Time Radiography

ABSTRACT

Real-time radiography is used for imaging both dynamic events and static objects. Fluorescent screens play an important role in converting radiation to light, which is then observed directly or intensified and detected. The radiographic parameters for real-time radiography are similar to conventional film radiography with special emphasis on statistics and magnification. Direct-viewing fluoroscopy uses the human eye as a detector of fluorescent screen light or the light from an intensifier. Remote-viewing systems replace the human observer with a television camera. The remote-viewing systems have many advantages over the direct-viewing conditions such as safety, image enhancement, and the capability to produce permanent records. This report reviews real-time imaging system parameters and components.

1. INTRODUCTION

PRINCIPLE

Real-time radiography is a nondestructive testing method using penetrating radiation in which the results are viewed concurrent with the radiation. In the case of dynamic systems, real-time radiography allows a radiographic interpretation to be performed simultaneously with the progress of the event. The arrangement of the radiation source, object, and image plane is similar to conventional film radiography. The essential element for real-time radiography is the conversion of the radiation to light by means of a fluorescent screen. The light signal may then be observed directly, amplified, and/or converted to a video signal for analysis and presentation on a television monitor and recorder.

Fluoroscopy is the original term used to describe the direct viewing of fluorescent screens. Real-time radiography or real-time imaging has taken on a predominate usage to describe modern industrial imaging systems.

Real-time radiography is often applied to objects on assembly lines for rapid inspection. Remote adjustment of the object position allows the inspector the freedom to review details of interest or pass on to other locations. Accept-or-reject decisions may be made immediately without the delay or expense of film development. For dynamic events, real-time radiography is typically used in the range

of several seconds to several minutes. Long-time events (on the order of hours) can be monitored. Short-time events may also be imaged in real time and replayed at slower rates. Television frame rates of 30 frames per second can cover events in the fraction of a second range. Flash radiographic events can even be imaged by using frame-grabbing techniques.

BACKGROUND

Real-time radiography had its roots in the discovery of x rays. Roentgen used phosphor screens for x-ray detection. Figure 1-1 shows the inspection of baggage at the Brussels railroad station in 1897. Barium platinoeyanide, willemitite, calcium tungstate, cadmium zinc sulphide, and cesium iodide are a few of the phosphors developed for fluoroscopy systems employed in medicine and industry over the years. Typical industrial applications in the first half of this century include the examination or inspection of golf balls, cables, candy bars, shoes, light alloy castings, and packages (O'Conner 1952, and Hampe 1956). Modern fluoroscopy systems still operate on the same principles, but with considerable improvements in the radiation sources, object handling, fluorescent

FIG. 1-1. European customs fluoroscope inspection in 1897.

screen performance, and personnel radiation protection.

The low brightness level of fluorescent screens is a significant disadvantage in fluoroscopy systems and requires the inspector to operate in a darkened environment for best results. Advances in the electronics industry have aided real-time radiography greatly. Image amplifiers and television systems were first introduced around 1950. Visual acuity improvements, no dark adaptation time, and image contrast improvements are all important technical

advances that image amplifiers have provided. The use of television systems has further advanced real-time radiography by allowing the inspector to be removed from the proximity of the object and radiation field. The digital electronic advances of the late 1960s and 1970s have opened considerably the possibilities of image enhancement and information storage. Remote operations with sophisticated image enhancement capability are typical of the modern systems.

2. FLUORESCENT SCREENS

PRINCIPLE OF OPERATION

Fluorescent screens basically consist of phosphor particles dispersed in a binder coated on a reflecting supporting base. As shown in Fig. 2-1, an x-ray or gamma-ray photon striking the screen perpendicularly along the axis Z excites a grain of phosphor at the point z, which emits a number of light photons. Typical paths followed by the photons are illustrated.

The probability that a light photon generated in the screen phosphor can leave the emitting surface depends on

- The number of scattering events incurred.
- The probability of absorption at each collision with phosphor particles.
- The depth at which it originates, i.e., on the x-ray stopping power of the phosphor.
- The spatial orientation of the free-path lengths between collisions.

FIG. 2-1. Structure of typical x-ray intensifying screen and the typical paths followed by light photons.

CONSTRUCTION AND MATERIALS

Fluorescent screens employ a variety of supports depending on the application. Typical screens have a white plastic or cardboard base approximately 0.4-mm thick as a support for the luminescent chemical layers. The screen base must be chemically inert so as not to react unfavorably with the luminescent material. It also must be uniformly radiolucent and cannot contain any inclusions of radiopaque substances that might cast a shadow on the fluorescent image. Also it must be durable enough for use in the radiation fields encountered in order to have an acceptable life span. The luminescent chemical (phosphor) is in the form of small grains. Grain size is a construction parameter affecting performance. The grains of phosphor material are combined with a suitable binder, usually a cellulose derivative, and coated on the support in a uniform layer. The final phosphor particle packing density is usually on the order of 50%. A protective surface is often added to resist markings and abrasive wear and also to permit cleaning.

In x-ray image intensifiers the fluorescent layer is deposited on the inside of the vacuum tube envelope. In this case, phosphors whose physical

properties are unacceptable for use in air can be employed. The depositing technique is often proprietary.

CHARACTERISTICS OF SCREENS

Fluorescent screens are characterized by their efficiency, spectral emission, persistence, unsharpness and gamma. Table 2-1 contains some parameters of potential screen phosphors.

TABLE 2-1. Phosphor parameters.

Phosphor	Density	Wavelength of peak emission	Decay constant
ZnS (Ag;Ni)	4.1 g/cm ³	450 nm	60 ns
ZnCdS (Ag;Ni)	4.5	559 nm	85 ns
CaWO ₄	6.1	430 nm	6 000 ns
CsI (Na)	4.5	420 nm	650 ns
Gd ₂ O ₂ S(Tb)	7.3	544 nm	480 000 ns

Efficiency

The overall efficiency of the fluorescent screen in converting x rays to light can be considered to be composed of three terms:

- The incident x-ray absorption efficiency η_a .
- The intrinsic absorbed x-ray-to-light conversion efficiency η_c .
- The light transmission efficiency, η_t , determined by the pathlength of light in the screen coatings.

Hence the overall efficiency is given by

$$\eta = \eta_a \eta_c \eta_t$$

The efficiency η_a , which is the fraction of the incident flux removed from the beam by the screen, can be calculated knowing the incident x-ray spectrum and the composition of the screen. The efficiency η_c is at least approximately equal to the efficiency of the phosphor under cathode ray excitation, which can be measured separately. The transmission efficiency η_t can be estimated if the scattering and absorption parameters of the screen are measured and if the boundary conditions at the surfaces are known. All of these efficiencies contribute to the speed of a screen; however, the maximum signal to noise ratio (SNR) is determined primarily by the absorption efficiency η_a . Table 2-2 presents some data for several CaWO_4 screens and a number of rare earth commercial screens (Wagner 1977).

Spectral Emission

The spectral emission profiles of phosphors can be an important parameter, depending on how they

TABLE 2-2. Fluorescent screen data at 80 kVp.

Screens	Absorption efficiency (%)
Fast CaWO_4	
Par	21
TI-2	33
Hi plus	39
Fast rare-earth	
Rarex-B mid speed	43
Rarex-BG mid speed	52
Lanex regular	69

FIG. 2-2. Spectral emission of several fluorescent screen phosphors.

are to be employed in a real-time system. Figure 2-2 is a plot of the spectral emission of four types of screens: CaWO_4 , LaOBr, $\text{Gd}_2\text{O}_2\text{S}$, and ZnCdS.

The effect of this spectral emission is demonstrated in Table 2-3 where the relative light yield for photopic response (the human eye) and an S-20 photocathode are compared at 140 kVp x-ray energy. The CaWO_4 and LaOBr screens which emit in the blue show an increase in response when measured with an S-20 photocathode over the photopic response, which is maximum in the green.

Persistence

The persistence of a fluorescent screen is the time over which it continues to emit light following excitation. The persistence curves are a characteristic of phosphors. Some curves have an exponential decay, whereas others have long decay tails. An estimate of persistence can be made by assuming an exponential decay and then assigning a decay constant that is the time for the phosphor to decay by a factor of 1 e. A few typical decay constant values are listed in Table 2-1. The persistence,

TABLE 2-3. Relative light yield as function of detector.

Screen	Photopic	S-20 photocathode
Siemens (ZnCdS)	100	100
BG Mid ($\text{Gd}_2\text{O}_2\text{S}$)	50	50
High Speed (CaWO_4)	7	32
Quanta III (LaOBr)	4	25

particularly with rapid-decay phosphors, can vary significantly depending on the purity and manufacturing process.

Unsharpness

Unsharpness in images formed by fluorescent screens is primarily a function of the grain size of the phosphor particles and the screen thickness, increasing as the parameters increase. Light transmission characteristics of the screen can also affect the unsharpness. Figure 2-3(a) demonstrates how unsharpness can affect the detection of a sharp-edged defect by spreading the edge shape. Here C represents the contrast in percentage of brightness change, d represents the observed defect width, and U represents the screen unsharpness. For a fixed value of U , a change in contrast C produces a change in the trace slope. It is apparent from Fig. 2-3(b) that when d is smaller than $2U$, the defect will vanish unless C_1 is above the minimum-observable contrast level. The following relationship may be easily obtained from Fig. 2-3(b):

$$d = \frac{2C_1 U}{C} \text{ for } C_1 \leq C \quad (2.1)$$

Typical values of screen unsharpness for commercially available screens vary from $U = 0.50 \text{ mm}$ to $U = 1.0 \text{ mm}$.

Screen Gamma

The fluorescent screen gamma is a measure of the contrast ratios between the output screen image brightness B and the input x-radiation intensity, I :

$$(\Delta B/B) = \gamma \frac{\Delta I}{I} \quad (2.2)$$

As in film radiography, the output image must provide a minimum brightness ratio between adjacent image areas for detection by either an observer or an image intensifying component. For most commercially available fluorescent screens at industrial radiography energies, the screen gamma is very close to 1.0, so the fluorescent screen itself is very seldom the limiting factor in an imaging system as far as the total system gamma is concerned.

FIG. 2-3. Effect of unsharpness on defect detection: U is screen unsharpness, C is contrast, d is dimension, and C_1 is minimum observable brightness difference.

EFFECTS OF RADIATION ENERGY ON EFFICIENCY

The efficiency of fluorescent screens is a function of the energy of irradiation. This is shown by the mass absorption coefficient versus energy curves of phosphor materials in Fig. 2-4. These data are calculated from the x-ray cross-section tabulations of Storm and Israel (1967). The K absorption edge is indicated by the step in the coefficient for those phosphors containing sufficiently heavy elements. The absorption efficiency for a screen is calculated by multiplying the coefficient by the phosphor density, packing density, and thickness, and taking the negative exponential.

Other than at the K absorption edge, the absorption coefficient (and hence efficiency), decreases with increasing photon energy. When dealing with machine sources of x rays, the spectrum of irradiation must be considered so that the total absorption efficiency η_a is found by integrating the absorption efficiency and photon intensity over energy.

The x-ray photon energy spectrum will be changed by the presence of an object. Lower energy scattered radiation is generated for which fluorescent screens generally have greater absorption

FIG. 2-4. Mass absorption coefficient of phosphors as a function of energy.

FIG. 2-5. Brightness as a function of peak x-ray kilovoltage for commercial fluorescent screens.

efficiency. The direct transmitted beam is simultaneously hardened.

The photopic brightness output of several types of screens as a function of peak x-ray kilovoltage is shown in Fig. 2-5. Similar data have been measured by Rossi and Hendree (1975).

Typical trends in screen conversion efficiency, as a function of energy for two common screen types are shown in Figs. 2-6(a) and 2-6(b). These are a sampling of data measured by Ludwig and Prener (1972) who used various radioisotopes for the photon source. Local variation in these trends will occur at photon energies near K edges of the phosphor material.

OTHER SCREENS

Fiber Bundle Scintillator

A type of fluorescent screen under development that offers considerable potential is the

FIG. 2-6. X-ray efficiency of (a) $\text{Gd}_2\text{O}_2\text{S:Tb}$, and (b) $(\text{Zn, Cd})\text{S:Ag}$ screens as a function of photon energy.

bunched fiber scintillator. Many small fibers are loaded with a scintillation material and bundled together as a light pipe. The length of the fibers determines the screen efficiency, which may easily approach 100% in a few millimeters. The resolution is determined by the fiber diameters. The difficulties in the development of such screens are the loading of the scintillation material and possible crosstalk between fibers. The scintillation material most widely considered is CsI.

Neutron-Sensitive Screens

Real-time radiography may be performed using neutron beams when the fluorescent screen is

sensitive to neutrons. High thermal neutron cross-section elements such as ^6Li , ^{10}B and Gd are used in neutron-sensitive screens. Plastic scintillation materials can be used in fast neutron radiography. The characteristics of the screen composition and construction are more important in neutron imaging than x-ray since the intensity levels of available neutron sources is generally lower than conventional x-ray sources. Of primary importance is stopping a sufficient quantity of neutrons to obtain an acceptable contrast level in the screen. Some data are available on screen brightness versus neutron flux for a variety of commercially available fluorescent screens applicable to neutron radiography. This data is presented in Fig. 2-7.

FIG. 2-7. Relative screen brightness versus neutron flux (Dahlke and Oien 1980).

Secondary Electron Emission

Some materials, when they absorb an x-ray, emit electrons in copious quantities. The phosphor materials used in fluorescent screens are in general more sensitive to electrons than the primary x-rays. At high x-ray energies, the electrons from suitable secondary electron emitters can be used to enhance

the imaging process. Heavy metals such as lead, tungsten, or tantalum can be useful in MeV radiography. Along with the production of secondary electrons to aid high energy detection, the heavy metal shields the phosphor from lower energy scatter radiation. This improves the contrast sensitivity of the image.

3. IMAGE QUALITY AND RADIOGRAPHIC PARAMETERS

INTRODUCTION

In real-time imaging systems that employ fluorescent screens, the factors that limit resolution are the same as in normal radiography; they only differ in weight. Table 3-1 shows some of the parameters and their interrelationships that affect image quality. The decisive factor is the storage time available. In radiography the x-ray photons absorbed in the recording medium during the long exposure times (minutes) are integrated for image formation. In real-time imaging, only the photons absorbed during the scan time of the image intensifier and output chain (or in the case of fluoroscopy, the summation time of the human eye (~0.2 s)), will add to each single image impression that may be evaluated. With the ever-increasing complexity and power of present imaging systems, the limit of ob-

ject thickness that may be penetrated as well as the extension and contrast of the details that may be detected are only limited by the quantum structure of the radiation and, of course, the noise introduced by each stage of the imaging process. Each detail, as defined by size and contrast, will be described by a number of radiation quanta that is proportional to the intensity of the radiation. The relative statistical fluctuation of radiation intensity in a two-dimensional element of area in the detector plane is proportional to the reciprocal value of the square root of the intensity. In general, radiation contrast in this image element must exceed the value of this fluctuation in order to yield a detectable image detail that may be distinguished from the background fluctuation. Progress in real-time imaging technology will show higher efficiency in screens with less internal unsharpness, which will lead to improved image quality.

TABLE 3-1. Image quality.

Contrast		Definition	
Subject	System	Geometry	Mottle
Thickness	Screen gamma	Source focal spot size	Quantum fluctuations
Scatter	Intensifier and/or camera gamma	Source-to-object distance	Screen grain
Radiation quality	Television monitor	Object-to-screen distance	Raster scan of the television monitor
		Screen thickness	
		Motion	

CONTRAST

Subject Contrast

Subject contrast is defined as the fractional change in brightness resulting from a change Δx in absorber thickness. The approximately linear relationship between screen brightness B in milliamperes and x-ray intensity on the screen I in roentgens per minute may be written as:

$$B = mI \quad (3.1)$$

or

$$\Delta B = m \Delta I \quad (3.2)$$

where m is the proportionality constant. The classical absorption law for monochromatic radiation is

$$I = I_0 e^{-\mu x} \quad (3.3)$$

or

$$\Delta I = -\mu I \Delta x \quad (3.4)$$

where μ is the linear absorption coefficient and x is the absorber thickness. By combining the above equations we have

$$\frac{\Delta B}{B} = -\mu \Delta x = \text{contrast (C)} \quad (3.5)$$

The effect of kilovoltage on subject contrast (C) manifests itself through the absorption coefficient μ , which varies with kilovoltage. The efficiency of the fluorescent screen affects subject contrast by its ability to convert the incoming x-ray photons to light and manifests itself through the screen brightness response B.

Observed Contrast

The observed contrast in real-time imaging is affected by several factors: screen response, the response of the image intensifying and projection system, and finally the visual response of the viewer. The observed contrast is treated in a very similar way to the subject contrast except that now one must include the effects of all of the system components. The usual method is to include a term γ_0 that is a measure of the contrast ratio between the output TV screen brightness B and the input x-radiation intensity I. This can be written as

$$\Delta B/B = \gamma_0 \frac{\Delta I}{I} \quad (3.6)$$

or

$$\Delta B/B = -\gamma_0 \mu \Delta x = \text{contrast (observed)} \quad (3.7)$$

where μ is the linear absorption coefficient, Δx is the change in the thickness of the absorber material and γ_0 is defined as the overall system gamma. In a system involving a sequence of image-transferring elements, the overall system gamma is equal to the product of the individual gammas of the sequential elements. Thus, for a vidicon television chain, for

example, the system gamma would be given by

$$\gamma_0 = \gamma_s \gamma_a \gamma_v \gamma_k \quad (3.8)$$

where

γ_0 = overall x-ray television system gamma,

γ_s = fluorescent input screen gamma,

γ_a = electronic amplifier chain gamma,

γ_v = vidicon tube gamma,

γ_k = television picture tube gamma.

For a typical case, the fluorescent screen gamma is taken as $\gamma_s = 1.0$, a conventional closed-circuit television amplifier chain provides a $\gamma_a = 1.0$ (maximum), the vidicon tube provides a $\gamma_v = 0.9$, and the television picture tube gamma is typically $\gamma_k = 3.0$.

Effects of Scatter

Scattered radiation affects contrast in fluorescent screens by effectively raising the background brightness level. The scattered radiation affects only the primary imaging component of a real-time system which is the fluorescent screen. Here the contrast is defined as

$$C = \frac{\Delta B}{B} = \frac{\Delta I}{I} \quad (3.9)$$

If, however, scattering is not eliminated, the equation for contrast becomes

$$C = \frac{\Delta I}{I + I_s} \quad (3.10)$$

where I_s is the scattered radiation intensity. Now, if $I_s = KI$, where K is the scattering factor, the equation for screen contrast becomes

$$C = \frac{\Delta I}{K + 1} \quad (3.11)$$

As this equation illustrates, it is important to keep to a minimum the scattered radiation impinging on the fluorescent screen in order to keep the contrast at an acceptable level.

Control of Scatter

Scattered radiation comes from many sources in a real-time imaging setup. There is room scatter, object scatter, fixture scatter, air scatter in the primary radiation beam, and scatter from any and all objects placed in the radiation beam. The control

of scatter in a real-time imaging setup is the same as in normal film radiography. Specific techniques to reduce scatter are:

- Collimate the primary beam to the minimum viewing area necessary.
- Shield the setup to reduce room scatter from walls, ceilings, and floors.
- Filter the primary beam to remove the low energy portion of the spectrum, which is more susceptible to scatter.
- Attempt to filter the radiation beam between the object and the fluorescent screen, because many filters remove the lower energy scattered radiation preferentially.
- Employ the use of antiscatter grids, both fixed and moving, between the object and the fluorescent screen when the resolution required permits such use.
- Use projection magnification to increase the distance of the fluorescent screen from the object scatter.

In general it is very important in real-time imaging techniques to carefully consider all areas where scattered radiation can be introduced and attempt to eliminate them or at least reduce their effect.

DEFINITION

Unsharpness

The penumbral image width, due to a finite focal-spot size q , is defined as unsharpness due to geometry U_g from Fig. 3-1(a):

$$U_g = \frac{b}{a} q = q(M - 1) \quad (3.12)$$

Here M is defined as the magnification factor and is shown schematically in Fig. 3-1(b).

It is generally agreed that penumbral images are not dependable. The limiting case for an umbral image is illustrated in Fig. 3-1(c), where

$$\frac{d}{q} = \frac{b}{a + b} \quad (3.13)$$

Here the defect width d is assumed equal to the defect depth Δx , where absorber thickness is x . From Eqs. (3.12) and (3.13) or from Fig. 3-1(c), it follows that for optimum definition $Md \gg U_g$,

while

$$Md \geq U_g \quad (3.14)$$

is the "minimal" definition on a perfect screen. In a similar fashion it can be shown that the minimum observable defect size d multiplied by the magnification factor M must be equal to or larger than the unsharpness U_g due to the fluorescent screen.

$$Md \geq U_f \quad (3.15)$$

The limit on definition is actually controlled by both types of unsharpness, so $Md \geq U_0$. According to Klasens (1946), the total unsharpness U_0 is equal

FIG. 3-1. X-ray image projection geometry: (a) geometric unsharpness U_g , (b) x-ray projection enlargement, (c) limiting condition for umbral image.

to the cube root of the sum of the cubes of the unsharpness due to geometry U_g and the unsharpness due to the fluoroscopic screen U_f ; hence

$$U_0 = (U_g^3 + U_f^3)^{1/3} \quad (3.16)$$

Optimum Magnification

X-ray projection enlargement is shown schematically in Fig. 3-1(b), where the magnification factor M is defined as

$$M = 1 + b/a = \frac{a+b}{a} \quad (3.17)$$

where a is the focal-spot-to-object distance and b is the object-to-screen distance. In general, due to the large inherent unsharpness of fluorescent screens, magnification of the x-ray image can be used to improve the radiographic definition. The optimum magnification M_{opt} (Halmshaw 1966 and McMaster 1959) for any screen unsharpness U_f and focal spot width q is given by

$$M_{opt} = 1 + \left(\frac{U_f}{q} \right)^{1/2} \quad (3.18)$$

The smallest observable defect d is then given by

$$d = \frac{U_f}{M_{opt}^3} \quad (3.19)$$

As is evident from Eq. (3.18) the focal spot size is an important parameter in defining the optimum magnification as well as the geometric unsharpness. Decreasing the focal spot size will improve the radiographic definition as well as allow larger magnifications. Unfortunately, in most commercially available x-ray machines and radiation sources, a decrease in focal spot size means a decrease in radiation intensity, which will then cause a decrease in brightness.

Effects of Motion

Normally in real-time imaging applications, an unsharpness due to the object movement can be a limiting factor in the radiographic definition. The factors that determine whether the object motion will seriously degrade the radiographic definition in real-time imaging systems are the x-ray excitation rate, the decay time of the fluorescent screen phosphor, and the delay time or imaging cycle of

the imaging system components. Typically, real-time systems are used with continuous or rapid (120 pulse/second) excitations, rapid decay phosphor (on the order of milliseconds or faster) and frame rates of 30 frames/s. The human eye requires about 0.2 s of integration time itself, so that it should be the limiting factor. Experience in fluoroscopy systems has shown that a practical maximum speed is on the order of 50 mm/s. It is a well known fact that the visual stimulus increases when movement occurs. Comparative motion attracts attention. This fact is easily demonstrated experimentally with a real-time imaging system.

Quantum Mottle

The statistical fluctuation of brightness on fluorescent screens due to the randomness of the production and absorption of x rays should be considered whenever the radiographic definition is considered. The process of the production and absorption of x rays is random and subject to statistical theory. Numerous sources of this fluctuation must be considered in any real-time imaging process. These include:

- X-ray photon production.
- X-ray photon absorption in the specimen.
- X-ray photon absorption in the screen.
- Conversion of x-ray to light photons.
- Fraction of light photons reaching the eye after transversing the imaging system.
- Light-photon absorption in the retina.

These fluctuations obey Poisson distributions such that the standard deviation s is equal to the square root of the intensity n :

$$s = \sqrt{n} \quad (3.20)$$

Because real-time radiography involves a series of processes, the standard deviation for the total sequence is

$$s^2 = s_1^2 + s_2^2 + \dots + s_n^2 \quad (3.21)$$

Certain stages in the process will cause either an increase or decrease in the intensity. It can be shown that to a first approximation

$$s^2 = gn \quad (3.22)$$

where g is the amplification of the process from the stage of lowest intensity to the final observation by the retina and n is the final intensity (Sturm and Morgan 1949).

To observe detail in the light image reaching the retina, there must be a sufficient intensity difference of the detail which is greater than the standard deviation. Thus

$$\Delta n = ks \quad (3.23)$$

where Δn is the smallest difference in the number of photons in the retinal image that can be detected and k is a constant termed the threshold contrast to standard deviation ratio. Contrast is defined as

$$C = \frac{\Delta n}{n} \times 100 \quad (3.24)$$

Then

$$C = \frac{k \sqrt{g}}{\sqrt{n}} \times 100 \quad (3.25)$$

Since n is the total intensity of photons in the retinal or camera image, it is equal to the number of photons arriving per second times the storage time of the detector t :

$$n_t = n \quad (3.26)$$

where

$$n_t = \frac{\pi d^2 n_0}{4} \quad (3.27)$$

Here d is the diameter of the object under observation and n_0 is the number of photons reaching the detector per unit area of the fluorescent screen per second. Now

$$C = \frac{2k \sqrt{g}}{d \sqrt{\pi n_0}} \times 100 \quad (3.28)$$

or rather

$$d = \frac{2k \sqrt{g}}{C \sqrt{\pi n_0}} \times 100 \quad (3.29)$$

The smallest discernible object size that can be detected is seen to improve with increasing contrast and number of stimulating photons. An image will be limited in detail sensitivity by statistical fluctuations as long as d is greater than the unsharpness of the system.

The statistical fluctuation of fluorescent screen brightness due to the randomness of the process is important at low brightness levels, which usually

occur with radioactive isotope sources or low intensity neutron sources for real-time imaging. Most industrial x-ray machines produce sufficient intensity of x rays so as to render the statistical fluctuations unimportant for most applications. With the advent of on-line digital processing of the real-time image, much of the effect of the quantum fluctuation from isotope sources can be removed in real time by video frame averaging or summing.

RADIATION SOURCES

The radiation source often plays the most important role in a real-time imaging application. Several points must be considered when choosing a radiation source for a particular real-time application. These include:

- What thickness and type of material must the source radiation penetrate?
- What specifically is intended to be imaged (e.g., hydrogenous material, defects in materials, specific components, etc.)?
- Is there sufficient radiation intensity to produce an acceptable fluorescent screen contrast?
- Is the radiation focal spot of an acceptable size for the image definition required?

X-ray machines have been employed for some time in real-time imaging systems due to their availability, ease of operation, high radiation intensity, and the large range of available focal spots. Gamma ray sources such as ^{192}Ir and ^{60}Co are finding increased use in the real-time imaging applications. Advantages include compactness and portability of the sources and ability to penetrate substantial thicknesses of material. Disadvantages include relatively low output intensity and larger focal spots. The relatively low radiation intensity can be compensated for somewhat with on-line digital processing techniques that can be applied to the output video signal of the imaging system. Some isotope sources are available with focal spots comparable to those found in conventional x-ray tubes, but again a reduction in focal spot size reduces the effective source strength and therefore radiation intensity.

Real-time neutron imaging is finding increased application in the industry with the advent of portable neutron sources, and nuclear reactors with beam ports suited to real-time imaging applications. Neutron sources are still expensive relative to other conventional radiation sources and sources other

than nuclear reactors suffer from relatively low intensity neutron outputs. Also, the effective focal spots of neutron sources are large. In most neutron sources, whether reactors, accelerators, or isotopes, the focal spot is defined by the collimator opening at the neutron source. In order to get a reasonable number of neutrons to transport down the beam tube, these collimator openings are necessarily larger than the focal spots possible in x-ray machines and high specific activity gamma ray sources.

Radiation Output Demand

The size and material of the part to be imaged will determine the radiation type and energy to be used. As a general rule, the type and energy of radiation should be selected so that the part thickness to be penetrated is five half-value layers. One half-value layer reduces the transmitted radiation intensity by 50%. Satisfactory results can also be obtained if the deviation from the rule is no greater than a factor of 2 (i.e., in the range of 2.5 to 10 half-value layers). The configuration of the part is of some importance because of the scattering characteristics of most materials. Configuration should also be considered when choosing a radiation source because it will affect the images obtained.

The half-value layer (HVL) can be equated with values of μx from the classical absorption law

$$I = I_0 e^{-\mu x} \quad (3.30)$$

or

$$\frac{\Delta I}{I} = -\mu \Delta x \quad (3.31)$$

Table 3-2 presents this data in tabular form. The detection percentage is based on a subject contrast of $\Delta x/x = 2\%$. The image contrast of $\Delta I/I$ is considerably increased for large thickness. This is a great advantage, provided that the transmitted energy is capable of being recorded.

TABLE 3-2. Half-value layers associated with different values of μx . Table from *Nondestructive Testing Handbook*, edited by Robert C. McMaster, Vol. 1, page 19-16, Fig. 11. Copyright ©, 1959, American Society for Nondestructive Testing. Reprinted/adapted with permission.

HVL	Values of μx	Detection $\frac{\Delta I}{I} \times 100$	Transmission $\frac{I}{I_0} \times 100$
1.45	1	2	36
2.17	1.5	3	22
2.89	2	4	13
3.42	2.5	5	8
4.33	3	6	5
5.05	3.5	7	3
5.78	4	8	1.8
6.50	4.5	9	1.1
7.22	5	10	0.6
7.94	5.5	11	0.41
8.66	6	12	0.25
9.40	6.5	13	0.15
10.01	7	14	0.09

4. DIRECT VIEWING FLUOROSCOPY

BASIC TECHNIQUE

The basic technique of direct viewing fluoroscopy systems is shown in Fig. 4-1. The radiation source, object, and screen are oriented in the same fashion as conventional film radiography. Often an optimum magnification is used, as discussed in Sec. 3. Following the fluorescent screen, a radiation barrier is provided to protect personnel. A cabinet arrangement containing the entire system is typical of most designs.

The advantages of fluoroscopy systems are low cost, simplicity, and speed of inspection. Relative to film radiography, the fluoroscopic unit has a higher capital investment. The operational costs however are quite small. The fluoroscope also provides the answer to the inspection question immediately. If the quality is in doubt, a technique of higher sensitivity may be applied to the area of interest in the object. Fluoroscopic units do not produce permanent records and suffer from limitations in detail sensitivity and resolution relative to film. The

operator must be dark-adapted to see the dimly illuminated screen and special care must be taken for operator safety. Finally, fluoroscopy systems are normally restricted to applications below 200 kV (63 mm of aluminum or 3 mm of steel).

RADIATION BARRIER WINDOWS

Consideration of the radiation exposure to the operating personnel of a fluoroscopic unit is a primary concern. The whole-body dose limit to per-

FIG. 4-1. Basic fluoroscopic cabinet unit.

sons working occupationally with radiation equipment is 0.1 rem/wk with a maximum of 1.3 rem/13-wk period (National Bureau of Standards 1954). The reduction of radiation exposure is accomplished with shielding windows that transmit the light information of the fluorescent screen, but stop the highly ionizing radiation.

In considering a radiation barrier window, the important characteristics are: x-ray absorption, optical transmittance, resistance to discoloration, and scattering properties. Table 4-1 lists the properties of some common barrier windows.

Lead glass is the most common window material. High density lead silicate glass has been found to be the most efficient window, while lead oxide (PbO) glasses have a protective coefficient directly proportional to the percentage of PbO. The protection coefficient, defined as the ratio of the thickness of lead to the thickness of material providing equivalent x-ray absorption, is used to evaluate the radiation attenuation. The lead equivalence is the commercial method of specifying lead glass. For example, a piece of lead glass 4-mm thick that has the same absorptive properties as 2 mm of metallic lead would be designated as 2-mm lead equivalent glass.

The optical transmittance of the window must be high and remain high in service. High radiation intensity will discolor PbO glasses as well as common glasses such as Pyrex. This normally occurs in the range of 10^5 to 10^6 rad, depending on the specific material. Fluoroscopy generally does not

TABLE 4-1. Radiation barrier window parameters.

Material	Density	Protective coefficient	Scattering ratio $\frac{I_s + I_p}{I_p}$	Tint
Lead silicate glass (Nuclear Pacific (iii D))	6.2 g/cm ³	0.55	1.01	Yellow
Lead oxide glass	5.1	0.26	1.06	Slightly yellow
Lead perchlorate (liquid window)	2.6	0.11	1.08	Clear
Lead plexiglass	1.6	0.05	—	Similar to acrylic resin

require dose levels high enough for this to be a problem. Discoloration can be removed in many cases by exposure to heat or infrared and visible radiation. The high density lead silicate glass will discolor under high radiation (excessive by fluoroscopy standards) but will recover in a matter of hours. Cerium stabilization can be used to prevent browning of lead glass under irradiation. Photosensitivity (permanent retention of an image) is a problem with some glasses.

X-ray scattering of the window is a further consideration. A few values for this were provided in Table 4-1, where I_s is the scattered radiation and I_p is the direct radiation (O'Connor 1952). The x rays scattered from the barrier back to the fluorescent screen will result in a general increase in brightness with a subsequent loss in detail visibility due to small brightness changes. Some evidence suggests higher lead content barriers may reduce the backscatter effect (Halmshaw 1966). Using a separation between the fluorescent screen and the window is one possible method of reducing this noise.

Liquid barriers are another possibility. A saturated solution of lead perchlorate is optically clear and resistant to discoloration, although it is hazardous (Cassen and McMaster 1945). Potassium iodide has been used successfully as a substitute for lead perchlorate (Curtis 1948-49).

Mirrors are another method of avoiding personnel exposure from fluoroscopy units. A loss of light and visual acuity does result. For high energy fluoroscopy (200 to 300 kV), the use of a mirror is generally preferred. In cabinet devices, the mirror and a lead glass barrier are both employed. Front-surface mirrors must be used to avoid ghost images which will develop due to multiple reflections in back-surface mirrors. A front-surfaced mirror commonly consists of a vacuum-deposited aluminum coating with a protective layer of silicon monoxide or magnesium fluoride. A visual reflectance of 88% is typical (Smith 1976). Periodic cleaning of the mirror, lead glass shield, and fluorescent screen is advised as a significant light loss can result from buildup on the surfaces.

OPERATIONAL CHARACTERISTICS

Factors Affecting Imaging

In fluoroscopy systems, the factors that affect the information obtained may be divided into two

categories: radiographic and physiological. Table 4-2 lists these factors.

TABLE 4-2. Factors affecting fluoroscopic image information.

Radiographic	Physiological
Source intensity	Sensitivity of the eye to low light levels
Focal spot size	
X-ray energy spectrum	Dark adaptation
Scattered radiation	Response to color spectrum
Geometric unsharpness	Experience of operator
Screen unsharpness	
Conversion efficiency	
Light emission frequency	
Light interference with protective barriers	

Visual Acuity

The operation of fluoroscopy systems typically occurs with light levels in the range of 1.0 to 0.0001 millilambert. The human eye uses two types of vision mechanisms: photopic (cone) vision and scotopic (rod) vision. The crossover from photopic to scotopic vision occurs around 0.02 millilambert. Industrial fluoroscopy is often performed with scotopic vision at less than 0.02 millilambert brightness level. The importance of the use of photopic or scotopic vision is shown in Fig. 4-2. This figure is a plot of visual acuity versus brightness, taken from Charabertlain (1942). The visual acuity (defined as the reciprocal of the angle between two contours in minutes) is shown to improve with brightness and shows a marked improvement with the transition from scotopic to photopic vision. At a brightness level of 0.1 millilambert two contours must be separated by a visual angle of 1.7 minutes to be distinguished. At a viewing distance of 0.25 m (10 in.) this would correspond to resolving 0.13 mm.

Visual acuity is a function of the wavelength of the light. The eye has a maximum response to 550-nm radiation, yellow light. Visual acuity is normally given for white light. In yellow or yellow green light the visual acuity of the eye is slightly higher. It is slightly lower for red light and 10 to 20% lower for blue or far red light. Figure 4-3 shows the sensitivity of the eye as a function of wavelength for photopic and scotopic vision (Smith 1963).

FIG. 4-2. Graph of visual acuity versus brightness.

FIG. 4-3. Relative sensitivity of the human eye as a function of wavelength.

Dark Adaptation

Dark adaptation is required when the screen brightness is less than 0.1 millilamberts. One minute of dark adaptation is required to detect a 1% contrast at 0.1 millilambert viewing level (Hecht and Hsia 1945). Dark adaptation is not just dilation of the pupil, but is an increase in retinal sensitivity. Scotopic vision is adapted in 10 min, but the eye will

continue to improve for at least 30 min. Twenty minutes of dark adaptation is considered good practice. Red light, thirty times brighter than white, will not affect dark-adapted eyes. The use of red goggles outside the viewing area and the use of red light in the viewing rooms are useful techniques to maintain eye sensitivity.

Contrast Sensitivity

The contrast sensitivity in fluoroscopy is a function of the x-ray absorption, screen response, and visual response. The contrast is given by $\Delta B/B = -\mu \Delta x$ as derived in Eqs. (3.1) through (3.5). The observed perceptible value of $\Delta B/B$ from Mees (1942) for brightness in the range of 0.001 to 1 millilambert is

$$100 \frac{\Delta B}{B} = 1.6B^{-0.38} \quad (4.1)$$

Substituting for $\Delta B/B$ and solving for the perceptible object contrast $\Delta x/x$, the percent sensitivity S in absolute value is

$$S = 100 \frac{\Delta x}{x} = \frac{1.6}{\mu x B^{0.38}} \quad (4.2)$$

Including the effect of scatter where $I_s = KI$, the sensitivity becomes

$$S = \frac{1.6(K+1)}{\mu x B^{0.38}} \quad (4.3)$$

This result indicates that the contrast sensitivity is improved as the brightness is increased. High power x-ray tubes can increase fluoroscopic sensitivity by increasing the brightness of the screen (Criscuolo and Polansky 1956).

The sensitivity in Eq. (4.3) is contrast sensitivity only and does not include detail. An equation for sensitivity presented by Halmshaw (1966) assuming cavities of depth = diameter = Δx is

$$S = \frac{3.65}{x} \left[\frac{1+K}{\mu M B^{1/2}} \right]^{1/2} \quad (4.4)$$

where M is magnification.

Scattered Radiation

When magnification is employed, scattered radiation effects are less significant because of the separation of the object from the screen. Without

magnification, the loss in image quality due to scatter effects can be severe. Grids could be used, but the brightness is reduced significantly. Of course good collimation of the beam should always be employed. Movable masks around the x-ray source to reduce the radiation field to the object size will remove bright glare from unshielded areas of the fluorescent screen.

Table 4-3 lists values of the scattering factor K for aluminum thicknesses for two types of fluoroscopic systems.

Magnification

Magnification can play an important role in improving the image sensitivity because of the large inherent screen unsharpness. The relation between magnification M , geometric unsharpness U_g , and focal spot size q was presented in Sec. 3. The optimum magnification is given as

$$M_{opt} = 1 + \left(\frac{U_f}{q} \right)^{1/2} \quad (4.5)$$

where U_f is the fluorescent screen unsharpness

An interesting experiment was performed by Halmshaw (1966) to evaluate experimentally the optimum magnification. The fluoroscopic image of a series of wires on specimens of varying thicknesses were viewed at various magnifications. The magnifications where the image detail was best determined to be the optimum magnification are shown in Fig. 4-4. The results are an average of subjective evaluations and are only applicable to the technical conditions of the equipment employed. Suggested reasons for these results are as follows:

- If the magnifications cause the unsharpness to be greater than the width of the image detail, the contrast is reduced.

FIG. 4-4. Experimentally determined curves of optimum values of magnification versus material thickness using a 0.3-mm focal spot x-ray source: (a) steel specimens, and, (b) aluminum specimens. Courtesy of R. Halmshaw.

TABLE 4-3. Scattering factor as a function of thickness (Halmshaw 1966).

Aluminum thickness (mm)	Object close to screen		With magnification	
	K	Brightness (millilambert)	K	Brightness (millilambert)
13	0.64	0.084	0.16	0.018
19	0.83	0.057	0.19	0.015
25	1	0.039	0.23	0.013
38	1.5	0.024	0.37	0.010
51	2	0.013	0.49	0.0051
64	2.7	0.0075	0.65	0.0025
76	3.4	0.0050	0.81	0.0012
89	4.1	0.003	1.0	0.0005

- The width of the unsharpness at the image of an edge is different for scotopic or photopic vision.

- The increase in image size that is useful may depend more on screen brightness than on unsharpness consideration because of the brightness versus visual acuity response of the eye.

In practice, large magnifications are often not practical. A reasonable magnification of 2X is often employed in equipment that will be used on a variety of objects. The use of magnification can also be helpful in the orientation of the x-ray source and screen distance. Whereas in the case of fluoroscopy without magnification the relation between source and screen distance is the same as in conventional radiography, for magnification techniques this limitation does not apply. The source-to-screen distance may be selected to provide the brightest screen possible with the most practical projected image size.

Experimental Sensitivities

Typically the sensitivity of fluoroscopy using a good technique is in the range of 2 to 5%. Using a high power fluoroscopic unit (4000 kVp-mA) Criscuolo and Polansky (1956) obtained sensitivities as low as 1.5% on aluminum samples from 19-to-76-mm thick. A 0.6×0.5 -mm focal spot, 2X magnification, and 460-mm source-to-screen distance was employed.

Movement

Movement of the object may take place not only to speed inspection, but to assist inspection. Often movement helps as a stimulus to observe contrast changes in the object that are not observed in a still image. For scanning, the maximum practical speed for high quality fluoroscopy is around 50 mm/s (Bates 1974). Most fluorescent screens have decay times that are rapid (10^{-2} s or less) with respect to the image retention of the eye. The critical flicker frequency at the light intensity levels used in fluoroscopy is around 60 Hz.

Statistical Considerations

Statistical fluctuations exist in the process of x-ray production, x-ray transmission, absorption in the fluorescent screen, light emission from the screen, and light absorption in the retina of the eye, all of which enter into the consideration of sensitivity (Cassen and McMaster 1945). Table 4-4 lists

a statistical evaluation of an industrial fluoroscopy system. The final statistic is 1.1×10^3 photons/mm². In this case the lowest intensity is at the last stage so that the statistical fluctuation is 3%. To achieve higher contrast sensitivity over a square millimeter area for this system would require changes in the statistical operation of one or more of the components.

RECOMMENDED PRACTICE

Good technique in fluoroscopy may proceed along two lines. One method uses a large focal spot tube because of the large inherent unsharpness of the screen. The other method uses a small focal spot and magnification. The geometry of both these methods should be optimized for the detail required in the object of interest. Typical x-ray tube-to-screen distance in a fluoroscopic unit is 380 to 500 mm. Collimation of the x-ray beam for reduction of scatter is very important. Variable diaphragms at the x-ray source and the viewing screen are useful. Of course a quality fluorescent screen is essential. High brightness with low unsharpness and emission in the yellow-green region are desirable.

For the inspector, constant brightness viewing is desirable. Changes in the background light intensity of the screen can affect the observer's interpretation. Constant brightness viewing of an object that may change in dimensions or material is achieved by adjustment of the x-ray kilovoltage and or tube current. The control for the x-ray machine should therefore be located at the viewing location. Automatic systems have been developed

TABLE 4-4. Statistics of an industrial fluoroscopy system.

X-ray production (2R/s at screen)	1×10^9 photons/mm ² /s
X-ray transmission of object (6%)	6×10^7
X-ray screen absorption (50%)	3×10^7
Light photons emitted by screen	1.5×10^{11}
Light photons reaching eye (250-mm distance)	1.9×10^5
Photons absorbed by retina (3%)	5.7×10^3
Photons absorbed per 0.2 s	1.1×10^3 photons/mm ² /s

to adjust the x-ray tube controls to a predetermined screen brightness for whatever object is placed in the fluoroscope.

The operator must of course be protected from the radiation field. A 250-mm distance from the screen to the operator is normal with sufficient shielding to reduce the radiation to an acceptable level.

APPLICATIONS

Fluoroscopy systems are used in industry today for rapid inspection of a variety of items. Light alloy castings are a prime application. Fluoroscopy is more often applied to determine product uniformity rather than flaws. The electrical industry, food industry, and explosives industry have considerable applications. Mail sorting and baggage inspection are other areas where fluoroscopy is quite useful.

5. REMOTE VIEWING SYSTEMS

INTRODUCTION

Remote viewing systems using a television pickup offer a significant advantage over fluoroscopy systems. The television display allows screen brightness and contrast to be adjusted by the operator. This improves visual acuity and allows

use in a lighted room so that dark adaptation is not necessary. Figure 5-1 is a block diagram of a remote viewing system. The fluorescent screen converts the radiation to light and an image intensifier boosts the light intensity to a level suitable for pickup by a television camera. The signal from the camera is sent to a television monitor located in a safe control

FIG. 5-1. Remote real-time radiographic viewing system.

location. A videorecorder is often used to provide a permanent record of the inspection—another advantage of this type of real-time imaging system over a fluoroscopy unit.

Shielding and mirrors are used to protect the electronic components from radiation. At x-ray energies below 1 MeV this is not a serious consideration for reasons other than good radiographic practice. Below 300 kV the intensifier and camera can be placed in the direct line of the radiation if desired. Typically, radiation damage occurs in electronics such as transistors at 10^5 rad, and will discolor optical components at 10^5 to 10^6 rad. Table 5-1 lists radiation damage threshold levels for a few components. Given time outside the radiation field, most materials will recover from the damage. Specialized equipment can be made such as camera tubes that will tolerate up to 10^6 rad. Glasses may fluoresce under strong irradiation, which can result in undesired light signals. Noise may also be generated in the electronics, increasing with the radiation intensity. Good shielding practice is desirable for mid-energy systems and is very important in high energy operations. Shielding for personnel protection is of course a necessary feature. The remote viewing system allows real-time radiography at very high energies where personnel shielding to observe a fluoroscopic screen directly would be impractical.

IMAGE INTENSIFIERS

X-Ray Image Intensifiers

The image intensifier tube converts photons to electrons, accelerates the electrons, and then reconverts them to light. Intensifiers typically operate in the range of light amplification factors from 30 to 10,000. The intensification is not necessarily solely electronic, but may include a reduction in area whereby the electrons from a large area input screen are focused on a small area output screen.

The earliest types of x-ray image intensifiers for x-ray applications were those described by Teves and Tol (1952) and Coltman (1948). Figure 5-2 shows both a Philips and Westinghouse design for this type of x-ray image intensifier tube. These tubes use a fluorescent layer inside the glass envelope to convert the x rays to light. Early tubes used zinc-cadmium sulphide layers. A photocathode adjacent to the fluorescent layer converts the light to elec-

TABLE 5-1. Radiation damage thresholds.

Silicon semiconductor	7×10^6 rad
Germanium semiconductor	5×10^4
Capacitors	$3\text{--}7 \times 10^8$
Resistors	$2\text{--}5 \times 10^8$
Ceramics, glass, optical elements	2×10^4
Plastics	2×10^4

trons. The Philips tube uses a 25-kV potential between the photocathode and output phosphor. Even though only 10% of the light photons from the fluorescent screen will generate electrons at the photocathode and 10% of the accelerated electrons will produce light at the output phosphor, a 10 to 15 times increase in luminous flux is generated by the acceleration. The tube has a 13-cm-diam curved input screen and a 1.5-cm-diam output. The nine times reduction in diameter from the fluorescent screen to the viewing screen provides an additional factor of 80 in brightness gain. The total gain is between 800 to 1200.

Technical improvements in electronic gain, fluorescent and photocathode layer efficiencies, and electron optics have made modern tubes of this type very useful in both medical and industrial applications (Vosburgh *et al.* 1977, Diakides 1973, Wang *et al.* 1977, Bates 1980, and Schagen 1981). CsI(Na) is now commonly used as the fluorescent layer because it has twice the x-ray absorption of ZnCdS and the crystalline structure minimizes lateral light diffusion. Rare earth phosphors such as Gd_2O_2S are also found to be superior to ZnCdS. It appears that at x-ray energies below 100 kV CsI(Na) is very good and at higher kV the rare earth phosphors may be more useful (Vosburgh *et al.* 1977). The hygroscopic properties of CsI(Na) have prevented its use outside the sealed-tube environment. Modern tubes are available with 23-to-25-cm input diameters, multiple modes (which electronically select variable field size of the input), and fiber optic output for direct camera coupling. A typical 21-cm-diam tube performs with resolution on the order of 4 line pairs/mm and gains on the order of 2000. Resolution is a maximum at the center of these intensifiers and decreases somewhat at the edges. A disadvantage of these tubes is that minification will increase image unsharpness. Also, because a length-to-diameter ratio of 1.0 to 1.5 is required for the electron optics, large diameter inputs require large

FIG. 5-2. Diagrams of two x-ray sensitive image intensifiers: (a) Westinghouse Fluorex, and (b) Philips.

tubes. This not only increases bulk but creates a potential implosion hazard. The curved input screens in these tubes cause inherent distortion. The tubes are sensitive to voltage drifts, stray magnetic fields, and space-charge defocusing at high dose levels (Wang *et al.* 1977). Electron scattering, thermionic emission, or light reflection on interior surfaces are causes of loss of contrast from intensifiers. Fabrication techniques try to minimize these problems.

Tubes as large as 36-cm input are now being manufactured by Philips (Kehl and Schrijvers 1977). The advanced vacuum tube technology requires a metal tube body. A titanium membrane is used for the entrance window to withstand atmospheric pressure and maintain transparency to x-rays. The titanium results in less scatter than a glass window which improves contrast. An acceleration voltage of 35 kV is used. Limiting resolution in the large format is specified at 3.6 line pairs/mm.

Image Converters

Another type of image intensifier, often called image converter, uses a light input and light output system. The electrons from the photocathode are accelerated by a high voltage and strike a phosphor screen. Luminous gains of 50 to 10^5 times are typical. Coupling of the tubes in stages can result in gains of 10^5 to 10^6 . Figure 5-3 shows three categories of image intensifiers. Typical input diameters for commercial tubes are 18, 25, and 40 mm. In Fig. 5-3(a) and (b) an electrostatic field directs the electrons. A fiberoptics faceplate minimizes the decrease in resolution near the edge of the tube. The fiberoptics is also good for coupling to other components of an optical system. Figure 5-3(c) shows a magnetically focused image tube. In this tube an axial magnetic field is used to provide good resolution and low distortion over the entire screen. The magnetically focused tubes are generally more expensive than the electrostatic tubes.

For radiography the light output from a fluorescent screen must be focused onto the input photocathode of the intensifier, using a lens or in some cases by direct physical contact. With a proper lens system, the image converter can be used with any size fluorescent screen. For a large input screen the loss of intensity that is experienced in focusing to the smaller diameter intensifier may be limiting, depending on the radiographic parameters. The term "image converter" is used because the light input and light output may not necessarily be at the same wavelength. Gain characteristics are often given as approximate values in this case because the input and output are actually over different spectrums.

Proximity Focus Intensifier

A proximity focus intensifier tube is one in which the separation between the photocathode and output phosphor screen is small. With a potential difference of several kilovolts, the electrons are focused directly across the gap. Resolutions of up to 40 line pairs/mm are possible. Proximity focusing x-ray intensifier tubes have been developed recently that provide a one-to-one, input-to-output size representation over large area images (25 cm) (Wang *et al.* 1977). These tubes use a CsI fluorescent input screen ahead of the photocathode.

Light intensity gains of 500 to 4000 are possible with resolutions between 1 and 2 line pairs/mm. An x-ray image intensifier of this type is much smaller

and lighter than the earlier described tubes. In principle, the unsharpness could be limited to the input fluorescent screen unsharpness with this design.

Channel Electron Multiplier

The channel electron multiplier or microchannel array is an assembly of small tubes for amplifying an electron signal using secondary emission. The channels are glass or ceramic coated with a high resistance material on the inside. A potential difference of 500 to 1000 V is applied across the channel. An electron entering the channel will strike a wall causing one or more secondary electrons to be released. These will continue to strike the channel walls yielding more electrons as they are accelerated by the electric field along the channel. The gain of the channel multiplier depends on the ratio of the length to diameter and the applied voltage. This allows multipliers to be made that are limited only by the technology to fabricate small diameter channels that will not break down under the electric field. With 1000 V and a length-to-diameter ratio of 50, a typical gain is about 10^4 . The resolution of the device is limited by the size of the channel spacing (Woodhead and Eschard 1971, and Link 1975). Figure 5-4 shows a diagram for a microchannel plate. The microchannel plate is often used in conjunction with the electrostatic image intensifier tubes to form what is called a second generation image converter. The microchannel array follows a first stage electrostatic lens.

Direct x-ray-sensitive microchannel arrays can be made. A metallic converter that emits secondary electrons following a high energy (200 kV and above) photon excitation serves as the input. These electrons are amplified in the channels (Charlmetron 1980).

Solid-State Image Intensifier

The solid-state image intensifier is a thin panel device that uses a photoconductor connected in series to an electroluminescent screen to produce an intensified image (Beal and Brown 1973, Hadley and Christiansen 1961, Kazan and Nicoll 1957, and Sarna and Wilburn 1961). When the photoconductor is stimulated by radiation, the electric field pattern is reproduced on the electroluminescent layer to yield an intensified visible image. Figure 5-5 shows a diagram of a panel consisting of an electrode, photoconductive layer, opaque layer, electroluminescent layer, and electrode layer. An AC

FIG. 5-3. Image converters: (a) single-stage electrostatically focused image intensifier tube, (b) three-stage electrostatically focused image intensifier tube, and (c) three-stage magnetically focused image intensifier tube.

FIG. 5-4. Microchannel plate.

FIG. 5-5. Solid state image intensifier.

age is applied across the panel, typically 10-15 kV or 200 V, and about 0.15 mA/cm². The input photoconductor must have an impedance per unit area that is much greater than the circuit impedance, but it must be sensitive to the range of input frequencies. If the impedance becomes comparable to that of the electron-cascaded layer, the input photoconductor must be constructed of a material with a low dark current, such as phosphor or polyester, Al₂O₃.

The efficiency of the solid state image intensifier is a function of the materials used, the input radiation, and the input geometry. Optical input intensifiers have low noise levels. The noise is not very satisfactory at low light levels. However, they can be used for video detection, where the photoconductor is sensitive enough to the radiation. If the device both converts the radiation to light and reconverts the light to light, then a fluorescent screen of sodium selenide, sodium sulphide, or silver chloride, with copper works well as a photoconductor for x-ray sensitive phosphors and fluorescent screens.

SPECTRAL MATCHING

Image intensifiers rely on a photocathode to convert input light radiation to electrons for operation. The x-ray image intensifiers have a fluorescent screen ahead of the photocathode to convert x-rays to light first. The spectral response and sensitivity vary among photocathode materials. Figure 5-6 shows the spectral response of several typical photocathodes. A high efficiency at the wavelength of light being observed with a low dark current are desirable characteristics.

The light emitted from the intensifier is generated by the action of electrons on a phosphor. The emission spectral characteristics of some common phosphors are shown in Fig. 5-7.

The spectral performance of phosphors and photocathodes is important for real-time radiography systems. The photocathode of the intensifier must be capable of functioning over the range of light emission by the fluorescent screen. Good matching of these spectra can make a significant improvement in system performance. Selection of the x-ray fluorescent screen must be based on the knowledge of the photocathode response of the light pickup system or the input phosphor of the light pickup must be specified to respond well to the light produced by the fluorescent screen. A further

FIG. 5-6. Photocathode response spectrum.

Phosphor	Material
P-4	ZnS:Ag + ZnCdS:Ag
P-11	ZnS:Ag(Ni)
P-20	ZnCdS:Ag
P-22B	ZnS:Ag
P-24	ZnO:Zn

FIG. 5-7. Phosphor spectrum.

consideration may be made to suppress certain wavelengths, since some phosphors emit promptly at one wavelength and decay with time at another. An advantage might be gained by matching well to the prompt light and poorly to the decaying signal. Generally, good spectral matching between commercial intensifiers and television systems exists.

STATISTICS

The image intensifier system can improve imaging by boosting the light output so that the statistical limitation in the image process is not at the eye, as in direct-viewing fluoroscopy, but is at the input fluorescent screen. The intensifier operates

on a statistical process itself for the generation of electrons and the regeneration of light. The sources of fluctuation are essentially independent so that Equations 5-1 and 5-11 apply. The amplification in Equations 5-1 and 5-11 is useful for improving detector systems with photointensifier systems is that when it takes the number of light quanta utilized by the detector, it is equal to the number of radiation quanta received from the input fluorescent screen.

TELEVISION CAMERAS

Principle of Operation

All electronic types of television cameras are based on the use of electron image pickup systems. Some of the major types of cameras are

the image orthicon, image dissector, image intensifier, and silicon intensified target tubes. Figures 5-8(a) and (b) show how the image of the scene on the input camera's function. The image of the physical object of the image orthicon forms the photoelectron pattern that is focused by the electron image tube. The then moderately "scanned" image. The photoelectrons striking the target cause secondary photoelectrons which are collected by the electron image tube and positive charges on the target. A second beam scans the target from the left, causing the positive charges to move. A third beam scans the electron image tube from the left, causing the electron image tube to move. The image of the scene on the input camera's function is the image of the scene on the input camera's function.

FIG. 5-8. Television cameras: (a) image orthicon, and (b) vidicon.

The image isocon is similar to the image orthicon. It differs by the capability to differentiate scattered and reflected electrons in the return beam. This results in excess current and consequently in a less sensitive response. The image isocon has improved the image orthicon's dynamic range to about 100 dB.

The silicon image orthicon is a rugged and simple tube. A vacuum tube with a light-sensitive photoconductive layer. A thin, negatively charged transparent layer is placed on the front of the photoconductive layer. An electron beam charges the target and the target is positive. When light is focused on the photoconductive layer, the target conductivity increases and the target charge becomes more positive. The electron beam to the electron beam strikes the electrons on the positively charged target and produces a positively charged signal at the output. The silicon image orthicon has a number of variations depending on the section of the photoconductive layer. The standard vidicon uses an antimony triphosphide layer. The plumbicon uses a PbS photoconductive layer, which provides faster response and higher contrast.

Another type of tube called the silicon intensified target (SIT) uses a photocathode as in image

sensor and focuses the photoelectrons onto a silicon mosaic diode target. Readout is similar to the vidicon. The design allows for very high light gains in the pickup by accelerating the photoelectrons to high energies (perhaps 10 keV) before striking the target. The SIT tubes and intensified SIT tubes (ISIT) have low light-level sensitivity.

Similar to the SIT tube are the secondary electron-conducting (SEC) tubes. A photocathode and an electrostatic focusing section are used ahead of the target. The target is a porous layer of KCl deposited on an aluminum and aluminum oxide base. Photoelectrons arrive at the target with about 8 keV of energy, dissipate their energy by generating secondary electrons in the KCl layer. The secondary electrons migrate to a signal plate having positively charged areas in the KCl. As the return beam returns the KCl to cathode potential. This current pulse is capacitively coupled to the signal plate whose current is used to develop a voltage across a load resistor to form a video signal.

Characteristics

The performance criteria for camera tubes are based on the sensitivity, modulation transfer function, limiting resolution, dark current, and lag.

FIG. 5-9. Television camera output versus light input. Adapted from *Electronics Engineer's Handbook* by Donald G. Fink, Editor-in-chief. Copyright ©1975 by McGraw-Hill, Inc. Used with the permission of McGraw-Hill Book Company.

Figure 5-6 shows a plot of signal output versus faceplate illuminance for typical tubes of the type discussed in Fig. 5-5. The slope of the curves is the tube gamma. The light source for illuminance is an *not an* of the response characteristics of the tubes

FIG. 5-6. Modulation transfer functions of television cameras. Adapted from *Electronics Engineer's Handbook* by Donald G. Fink, Editor-in-chief, Copyright © 1975 by McGraw-Hill, Inc. Used with the permission of McGraw-Hill Book Company.

Modulation transfer function data and limiting resolution as a function of faceplate illuminance are given in Figs. 5-10 and 5-11. Table 5-2 lists the characteristics for typical tubes in the categories discussed. Lag is given as the percentage of the original signal present after three fields of exposure.

In x-ray imaging applications image isocons of ten are the most desirable television camera tubes. Unfortunately, isocons are very expensive. Vidicons are commonly used in combination with x-ray-sensitive image-intensifier tubes. SIT tubes are experiencing more usage and the plumbicon type of tube is valuable when minimum lag is desired. The cameras must be matched in light pickup sensitivity to the fluorescent screen light intensity by x-ray intensity adjustment, fluorescent screen efficiency or intensification techniques. Scanning rates of the camera tubes are typically 30 frames/s standard. In some applications where very low radiation intensities are experienced, it is feasible to use a slower scanning rate. The target of the television camera can be made to integrate the incoming signal for several minutes and then be scanned to provide one frame of information. SEC cameras are often used in this type of application.

FIG. 5-11. Limiting resolution of television cameras. Adapted from *Electronics Engineer's Handbook* by Donald G. Fink, Editor-in-chief, Copyright © 1975 by McGraw-Hill, Inc. Used with the permission of McGraw-Hill Book Company.

where B is the luminance of the output phosphor, T is the lens transmission, f is the f number, and M is the magnification. The lower the f number, the more light collected for imaging. Simple lenses are not often used in coupling because of the low optical efficiency. For example, if a reduction in image size by a factor of 2 is required in the coupling, the phosphor-to-lens distance must be twice the lens-to-pickup-surface distance. From the lens formula, the phosphor-to-lens distance will be three times the focal length and will have poor light collection efficiency. With a one-to-one coupling, this distance is still twice the focal length. Collimated optics is superior because the objective lens, focused at infinity, is located at its focal length from the phosphor. Collection efficiency is nine and four times greater, respectively, for the two magnifications just discussed. The second lens will determine the image size at the pickup surface by the ratio of its focal length to the objective lens focal length. Vignetting, which is a reduction in light intensity at the edges, does occur in collimated optics. This is minimized when the lenses are close to each other. Some real-time imaging systems use specialized optics such as the Bouwers/Schmidt lenses. They are used in a concentric mirror arrangement in systems, such as the "Delcalix" real-time imaging system to allow a large-diameter input (320 mm) and a low (0.65) f number.

Fiber optics is another coupling technique. Intensifier tubes often use fiberoptic input and output surfaces. These surfaces may be coupled directly to other components that have similar surfaces using an optical gel between them. Fiberoptic light guides may also be considered to move light from one location to another such as from the fluorescent or phosphor screen to the camera. The potential advantages are greater retention of the light, one-to-one size transfer, improved contrast by suppression of undesirable reflections, and shortening of the system dimensions. The use of fiber optics over considerable distance or around unusual obstructions is also a possibility. Fibers for fiberoptic systems are glass or plastic of diameters of 1 or 2 μm to 50 μm . The fiberoptic array operates on total internal reflection. Each fiber is coated with a lower index of refraction material to reduce leakage. Losses in the fiberoptic system are mainly due to the opacity of the fibers in long systems or the acceptance angle of the light in short lengths.

VIEWING AND RECORDING SYSTEMS

Television Monitors

Television monitors for observing the video signal are cathode ray tubes which use a modulated electron beam to write on an output phosphor. In the United States the standard format is 525 lines, interlaced. The interlacing means that the total picture frame is composed of two fields. The first field uses every other line on the screen and the second field writes between the first set of lines. The television camera provides the monitor with the appropriate operating format in the video signal. Other systems are used routinely in Europe and have various numbers of lines which can be as high as 1200 lines, triple interlaced. The tubes vary in size, deflection system, and component design. Contrast controls can be adjusted to increase or decrease the gamma over a range of values, typically 0 to 10.

To see an object, there must be a sufficient number of scan lines in the television image. Siedband (1971) presents the following description of scan-line requirements. To visualize n objects there must be $2n$ lines. Allowing for random orientation, this should be increased by a $\sqrt{2}$ factor. To see a mesh with 50 holes/cm would require 140 lines/cm scan rate. Horizontally, the resolution is determined by the bandwidth of the signal. One cycle of bandwidth (one-half cycle for the object and one-half cycle for the spacing between objects) is required to see an object. In a conventional system the viewing matrix uses a 3×4 aspect ratio, the horizontal being larger in size than the vertical. If 525 scan lines are used, then the horizontal will require $4/3 \times 525/\sqrt{2}$ half-cycles or about 250 cycles to maintain the same resolution. Using 30 frames/s scanning and a factor of 1.2 for retrace time, the required bandwidth is on the order of $525 \times 250 \times 30 \times 1.2 = 4.7$ MHz.

Although it may appear that resolution could be improved by increasing the number of scan lines, two problems result: the charge capability on the target elements of the camera will be reduced in proportion to the area change, which may reduce the sensitivity, and an increase in bandwidth will be required, which increases the noise in the electronics in proportion to the square root of the bandwidth. The result is that the standard number of scan lines

is often as good as or superior to higher scan line systems (Siedband 1971 and Webster 1971). Many cameras and television monitors are designed for higher bandwidth operation (10 MHz and greater). In quality systems this provides greater resolution horizontally (800 lines or more) than vertically. Since the standard 525-line vertical is used so commonly, resolution of video systems is often quoted by the horizontal resolution value, which is a function of bandwidth.

Recording Equipment

Recording the video signal makes for a permanent record of the radiography. Videotape records are the most common method. These recorders may be either reel-to-reel or cassette type. The reel-to-reel recorders offer long time recording; reels with lengths to many hours may be used. The tapes may be conveniently cut and spliced for presentation. Cassette videotape recorders are more easily operated than the reel-to-reel machines for loading, unloading, and storage of the tapes. The cassettes are usually limited to 1 hr. The signal-to-noise ratio of the record will improve with the width of the tape, which varies from one-half to two inches.

Both reel-to-reel recorders and cassette videotape recorders may be equipped with pause and slow motion modes. The pause mode, however, only shows one field rather than the full frame. This results in a reduction of information by one-half. Expensive recording equipment is available that repeats the first field of information as the second field in the stop mode. This improves the visual display, but still represents a reduction in information. The reason for showing only one field is to eliminate interfield jitter caused by movement between field scans of the camera. Slow motion modes are quite useful for replaying rapid events. Unfortunately in slow motion replay, a broadband synchronizing signal is reproduced on the video screen sweeping by at each frame. This is not easily removed and can be very distracting in evaluating images; removal of the synchronizing signal noise is available with expensive video replay equipment.

A videodisk is another possibility for storage of real-time radiographic information. The videodisks are expensive and are normally only used for recording short periods of data such as 600 frames. The quality of the videodisk can be excellent. The videodisk will play back either forward or backward, slow or fast, and step forward or

backward one frame at a time. The full frame of information is available in the stop mode of some data handling video disks; however most instruments play back only one field, producing it twice in order to avoid interfield jitter. For short duration events for which a high quality record for slow motion analysis is desired, the videodisk is an excellent method.

All video recording devices alter the video signal in some way. When linking the output of the recording camera to monitors and recorders, the strength of the signal is reduced in proportion to the number of devices. This results in a weaker signal at the recorder and a poorer record. Repeated copying results in a degradation of the image as the signal becomes successively reduced. Playback from recorded images will be inferior to the original image. It is also important to consider the bandwidth capability of recording equipment. It should be matched to the bandwidth required in the original image to maintain as much information as possible. The standard television broadcast bandwidth is 4.2 MHz to which many video recording devices are matched. However, videotape units to 10 MHz and videodisks to 6 MHz are available and may be extended in bandwidth in the future for specialized applications.

Hardcopy

Hardcopy is often desirable. This is normally the need for a single-frame image. If the real-time radiograph is of a static object, photography of the television monitor is suitable. If the photographic exposure time integrates over many frames, the result will be superior in image quality to the video monitor display. Gray scale printers are also available which reproduce video pictures on paper. Twelve to 16 gray scales are typical.

For events involving motion, the frame of interest must be stopped to be taken for hardcopy. Pause modes on videorecorders can be used for this. Another method is the kinescope, which records video information onto 16-mm movie film. The self-contained unit synchronizes the film frames to the video frames displayed on its internal monitor. The movie record is the hardcopy. Similarly, movie records may be made using cineradiography. A motion picture camera is focused on the output phosphor of the image intensifier for this technique. Optics which split the output light signal can be used so that both television viewing and

cineradiography may be performed simultaneously. Cineradiography generally provides better image quality than that obtained with a kinescope (Webster *et al.* 1967). A kinescope, because it does view a bright video screen, can generate output onto film at lower x-ray exposure levels than can be obtained with cineradiography.

A number of electronic devices exist on the market which will grab frames. This can be performed in an analog mode or may involve a digitization of the frame. Hardcopy can be obtained when the output of these devices is displayed on appropriate storage scopes and then processed through printer units.

SYSTEM EVALUATION

Penetrimeters

The most common method of evaluation of radiographic sensitivity is the use of a penetrometer or image quality indicator. The penetrometer is a thin plaque of the same material as the object. The plaque thickness is a certain percentage of the object thickness. The penetrometer has holes of diameter 1, 2, and 4 times its thickness. The radiographic quality of the imaging system is listed as the smallest percentage penetrometer detectable and the smallest hole detectable. Other types of penetrometers are in use, such as the DIN penetrometer in Europe. This penetrometer uses wires of graded diameters and the same material as the object. The size of the smallest wire detected determines the quality level.

Many experimenters use their own measurement systems for evaluating the quality of an imaging system. These are generally called image quality indicators (IQI). IQI's vary in design, but commonly they contain a step wedge of material from which the smallest percentage change in material or contrast level can be determined. Resolution may be measured by the smallest hole size detectable. Since the ability to observe a certain diameter hole is a function of the depth of the hole, it is common to specify the resolution for a high contrast object.

The use of wire meshes to evaluate real-time imaging systems is also a common technique. The wire mesh is an object whose fine structure is repetitive. Wire meshes are often used to indicate the quality level of inspection at certain speeds of movement.

Modulation Transfer Function

Another method which is more rigorous in its approach to understanding the imaging system is the modulation transfer function (MTF). The MTF is the ratio of the image amplitude to the object amplitude as a function of sinusoidal frequency variation (ω) in the object:

$$\text{Sine wave response } (\omega) = \frac{I(\omega)}{O(\omega)}$$

where $I(\omega)$ is the image amplitude and $O(\omega)$, the object amplitude.

This can be visualized by considering a bar pattern. As the pattern becomes finer and finer, the image response begins to lose contrast. A plot of the response, called square wave response when a bar pattern is used against the frequency of the bars and spaces is very similar to the MTF. Square wave response factors can be used to evaluate systems, and under certain conditions can be corrected to the sine wave response or MTF equivalence (Coltman 1954 and Bossi *et al.* 1972).

The true MTF, generated by an object having sinusoidal variations in intensity, is measured routinely for optical components such as lenses, intensifiers, and cameras. For radiography such an object is normally prohibitively difficult. Instead, the MTF is derived by generation of the edge spread function, differentiating to obtain the line spread function and Fourier transforming to yield the MTF. Derivations of this and examples may be found in the literature (Mees 1942, Morgan 1962, Morgan *et al.*, 1964, Smith 1976, and Klingman 1971). The importance of the MTF in evaluating systems is that the total system MTF is the product of the individual MTF's of the components:

$$\text{MTF}_{\text{system}} = \text{MTF}_1 \times \text{MTF}_2 \times \text{MTF}_3$$

This is shown in Fig. 5-12 where the modulation transfer functions for the fluorescent screen, optical coupling, image orthicon camera, and total system are shown (Halmshaw 1970 and 1980). The usefulness of this method is obvious. The components of a system are analyzed quantitatively; the poorest is easily determined. A proposed system's performance may be predicted from data on the individual components.

FIG. 5-12. Modulation transfer function of a system. Courtesy of R. Halmshaw.

IMAGE PROCESSING

Video display images are ideal candidates for image-processing techniques. Image-processing techniques can be applied in real time or as a post test image-enhancing or coding process. Some level of image processing on most video images will generally improve the quality since the short (33 ms) exposure per frame often results in a statistical limitation in image quality. Typical processing techniques to reduce this statistical limitation are frame averaging and frame summing. Other processing techniques which can be useful are edge enhancement, contrast stretching, polarity inversion, and color coding. The type and degree of image processing required depends on the information

required from the video display images as well as the image format required for viewing or data presentation. Modern image-processing techniques use digitization almost exclusively. In addition to local processing, this allows the option of transferring the image to large mainframe computers for sophisticated image processing.

SYSTEM DESIGN

Modern remote-viewing systems for general purposes usually involve two types of systems: x-ray image-intensifier and vidicon camera, or a fluorescent screen-low light level isocon camera combination. Additional equipment should include a quality video monitor, a videotape recorder, a videodisk for dynamic recording, a frame digitizer and image-enhancement device (512 × 512 with 8 bits, available for real-time summing, running average, contrast adjustments, frame grabbing for edge enhancement, and subtraction techniques), and a hardcopy system.

The x-ray image-intensifier systems are usually less expensive than the isocon camera systems. They operate best at the x-ray energy for which they are designed. These include low and intermediate energy systems and additionally there are now systems suitable for mega-electron volt radiography. The isocon camera systems are more versatile. Since the fluorescent screen is changeable, the system can be adjusted for optimum performance at any energy. Both systems can perform in the 1.5-to-2% sensitivity range. The resolution limit will generally depend on the input field size, video bandwidth employed, and input phosphor.

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