

## Modern methods of industrial radiology – a review

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This review divides roughly into four parts: (1) Radiography-on-film; (2) Radiographic imaging using non-photographic materials; (3) Radioscopic (fluoroscopic) methods; (4) Computed radiography (CT). The physics of image formation is common to all these, and the factors limiting image quality and so flaw sensitivity, are discussed. Image digitisation and computer control, image enhancement and image interpretation are also now common to all these methods and are discussed. The capabilities and limitations of radiological methods for material evaluation are discussed and the inherent limitations outlined.

### 1. Radiography-on-film

Classic radiography-on-film methods were developed more than fifty years ago and it would not be far from the truth to suggest that the best high-quality radiographs taken in the 1950s could not be bettered today. It is true that we can now radiograph a larger range of metal thicknesses and can have shorter exposure-times, but the basic physics of the techniques has not changed fundamentally. There are, of course, many new developments, some very important, and I will come to these later, but first I want to go back to fundamentals because some of them are not yet universally understood and are applicable to almost all industrial radiography.

A radiographic image on a film consists of a series of areas of varying blackness/greyiness which are seen when the processed film is laid on an illuminated screen of suitable brightness. The usual term is photographic density (a film of density 2 transmits 1/1100 of the incident light) and as this is a typical working film density screens of very high luminance are desirable for film viewing (around 3000 cd/m<sup>2</sup> is typical). If the screen is not sufficiently bright, the human eye literally cannot discern all the detail in the film image. This in fact, is a vitally important point in a radiographic technique (i.e. screen brightness related to film viewing conditions). A radiograph is taken

by placing a suitable source of radiation at a distance on one side of the specimen and the film (in a light-tight holder – the film cassette) on the other side of the specimen, usually close to the specimen. The source of X-rays is the focal spot on the X-ray tube, usually 2-3 mm in effective diameter or a gamma-ray source of similar size. There are also minifocus and microfocus X-ray tubes with much smaller focal spots: more of these later.

X-rays and gamma-rays travel in straight lines; they cannot be focussed usefully at the energies used in industrial radiography, so the set-up for taking a radiograph is as shown in Fig. 1A. Thus, an image of a cavity in a specimen is projected on to the film at very slightly greater than real size. In Fig. 1B the width of the X-ray source has been exaggerated for clarity and it is obvious

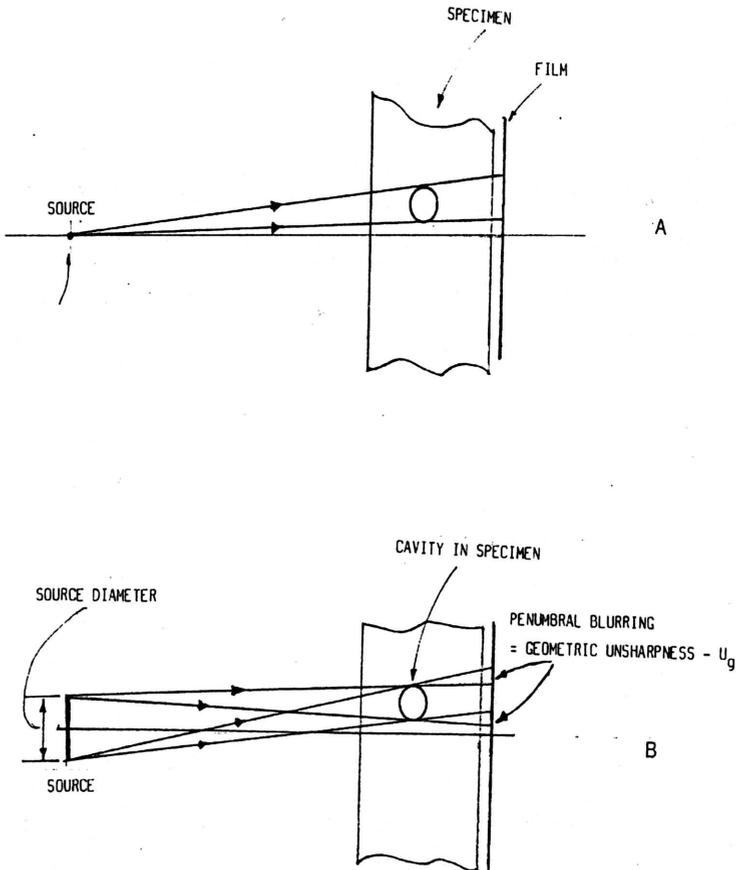


FIGURE 1. Basic set-up for conventional radiography, A – assuming a point source of radiation, B – with a larger source of radiation (exaggerated for clarity) to illustrate geometric unsharpness.

that when one examines the image of a flaw in the specimen which is not very close to the film that this image is unsharp (blurred) and that the amount of blurring depends on the source-to-flaw distance, the flaw-to-film distance and the source diameter. This blurring is called *geometric unsharpness*  $U_g$  and in practice will typically be anything between 0.5 and 0.02 mm.

It is partly under the control of the radiographer in that he can reduce it by using a larger source-to-film distance or a smaller source diameter, but both these methods are likely to increase exposure-times. Many Standards have been written since about 1935 to the present day, recommending suitable geometric unsharpness values for different applications and specimen thicknesses. Some of these are practical and realistic; some in my opinion, are questionable.

In industrial radiography we use X-rays which are generated by applying a high kilovoltage across the anode/cathode of an X-ray tube and this kilovoltage may be anything between about 10 kV and 20 MV, most work being done with 100-300 kV X-rays. (All industrial radiographers use kV, never wavelengths, to describe X-ray energies). Obviously the higher kilovoltages are needed to produce some transmitted radiation on to the film with denser and thicker specimens; again there are Standards. A radiographic film emulsion consists of a larger number of closely packed silver halide grains in a gelatin emulsion and when an X-ray quantum of greater energy than about 33 keV is absorbed in one halide grain it produces a secondary electron which can have enough energy to travel in the emulsion to another halide grain and sensitise it, so that the image formed is not a 'point' the size of one silver halide grain but a disc (volume) formed by a bunch of grains. In addition, when an exposed halide grain is chemically developed the resultant silver is no longer microscopic, but consists of a small volume of filamentary silver of the order of 0.1 mm. The result of all this is an unsharp image solely due to the emulsion characteristics and the radiation energy and is called film unsharpness or inherent unsharpness ( $U_f$ ) and if it is measured in the same way as for geometric unsharpness, its size is between 0.05 mm (low energy X-rays) and 0.6 mm (high energy X-rays) [1], so high energy radiographs are always unsharp. In industrial radiography the specimen is always static and the equipment rigid, so there should be no movement unsharpness as in medical radiography. I have gone into this in considerable detail as the same considerations hold for all radiological imaging techniques whether with film or not, with different causes of unsharpness.

One final point on this topic, which is not always understood. Radiographic unsharpnesses are not arithmetically additive:

$$U_g + U_f = U_{\text{total}} \quad \text{is not correct,}$$

$$U_g^2 + U_f^2 = U_{\text{total}}^2 \quad \text{is near the correct value.}$$

Coming now to the radiographic image, this can be described, as with other optical images, in terms of three parameters: contrast, sharpness, noise.

**Contrast** is almost self-evident. If there is a large difference in brightness between the image of a detail and the background, this is higher contrast. If the image is low contrast there is a danger that it might not be discerned and that shallower defects in the specimen are not seen on the image. Radiographic contrast depends on a number of technique parameters – X-ray kilovoltage, quantity of scattered radiation reaching the film, film contrast, viewing conditions, etc and is fairly well understood. With good film viewing equipment a density difference on a radiograph of 0.01 (i.e. a contrast of 2.3%) should be discernible.

The **sharpness** of a film radiograph is measured as radiographic unsharpness in mm; in radiography-on-film this is the combined effect of geometric and film unsharpnesses. Resolving power and modulation transfer functions (MTF) are used to specify the performance of more complex radiological systems such as radiosopic equipment, where there are additional causes of unsharpness, but are not generally used to describe film techniques.

**Noise** in film radiography is film graininess (granularity when measured, graininess when observed by eye). Because the film integrates the transmitted radiation over the exposure-time, quantum noise is normally negligible, although with very high energy X-rays in the megavoltage range there is some evidence that quantum noise can be seen on the radiograph.

Granularity on a radiographic film is very difficult to measure and has caused much controversy. Emulsions are coated on both sides of the film base and are thicker than on a conventional photographic film, so while there have been a few attempts to measure film noise by a Wiener spectrum [2] the more practical method of scanning a film of uniform density with a small aperture and recording the local RMS fluctuations in density ( $\sigma_D$ ) has been adopted. Quite recently, a European Standards Committee [3] has proposed a scanning spot of 100 micrometres to scan a film of density 2.0. It is claimed that OD correlates closely with film graininess and that values of  $(G/\sigma_D)$  can be used as a film quality index and a measure of the signal/noise ratio.  $G$  is the film gradient at density 2.0.

For many years radiographic film manufacturers have produced a range of films of different speeds and graininess, popularly described as “fast, medium-

speed, finegrain, very-fine-grain, etc.” without any quantitative description of their characteristics, except speed. EN-584-1:1995 tables six film classes C1-C6 as shown in Table 1, in terms of gradient (contrast),  $G/\sigma_D$  and  $\sigma_D$  (max), and all the EN Standards for film radiography [4, 5] are written in terms of these six film classes. This system is not yet fully accepted. The USA has a similar system but with eight film classes. Present-day European Standards for radiography (EN444, EN1435) specify only two techniques – ‘basic’ and ‘improved’ and these specify only four of the six film classes, so that high quality techniques using the slowest film (class C1) are not detailed.

Most Standards and Codes of Good Practice, including the EN Standards, specify the use of some pattern of Image Quality Indicator (IQI). This is a device which contains wires of different sizes, or holes drilled into a thin plate, which is placed on the specimen and the discernibility of the holes or wires is taken as a measure of the IQI sensitivity. This IQI sensitivity is assumed to have some relationship to flaw detectability in the specimen. There are three patterns of IQI standardised in Europe and another in the USA and I understand that some other countries still use their own patterns. Two of the patterns use holes, or wires of the same material as the specimen, but a special duplex wire IQI is also specified using high density wires; this is for special purposes and is used mainly for radioscopic applications. It is common practice for a Standard for (say) weld inspection to specify that the wire IQI sensitivity shall be better than (say) 1.5% of the specimen thickness, or that a specific wire diameter be visible on the radiograph.

The philosophy of radiographic standards varies considerably from one country to another. Some detail all the technique parameters, others specify an IQI value to be obtained and leave the technique details to the radiographer. American philosophy is generally different from European practice in that in some Standards an acceptable sensitivity is quoted in terms of the use of the ASTM plaque type IQI (drilled holes of different diameters) and no other detail of technique is specified. Most European codes specify technique details and acceptable IQI values. In the author’s opinion, unnecessary problems have arisen in writing CEN Standards for radiographic inspection using film, by attempting to write one general Standard covering all metallic materials, all metal thicknesses, all radiographic equipments, and also limiting the detail to only two inspection classes – ‘basic’ and ‘improved’. Much better techniques with better flaw sensitivities are quite practical on many thicknesses of material with modern X-ray equipment.

The other major unresolved problem in film radiography is the assumption that IQIs represent real flaws. Almost universally IQIs are either drilled holes, usually of diameter = height or fine wires and whereas a drilled hole might be considered to approximate to a gas hole in a weld or a casting, a

round-section wire does not resemble any sort of weld or casting flaw. The most significant metal flaws, from the point-of-view of materials strength and tendency to failure, are obviously cracks or welding flaws such as lack-of-fusion, and the ability to detect these flaws is in no way related to IQI sensitivity. A suggestion which one still sometimes finds in the literature, that ability to detect a wire of diameter equal to 1% of the specimen thickness means that a crack of this dimension can also be detected is complete rubbish.

In summary then, for radiography-on-film today we now have:

- Equipment up to about 300 kV which is robust, reliable and relatively cheap.
- More expensive equipment from 300-500 kV.
- High energy X-ray equipment from 1 MV to 20 MV, which is almost always, today, an electron linear accelerator (linac). These are very expensive in both capital and installation, but are essential for the radiographic examination of steel greater than 120 mm thick. They are widely used on austenitic steel items.
- Microfocus X-ray equipment up to 300 kV with effective X-ray sources of the order of 10 micrometres, which allow the production of enlarged images of small objects with a geometric unsharpness which can be made negligibly small. The X-ray output of these microfocus tubes is low, so exposure-times are longer and their use in radiography-on-film has so far been limited and relatively unexplored.
- Nearly all gamma-radiography is still done with Ir-192 or Co-60 sources, as it was 40 years ago, but the design of containers, from the safety point-of-view, has greatly improved. A few new radioactive materials are now marketed for gammaradiography in specialised applications – Yb-169, Se-75.
- There are a series of CEN Standards designed to cover all radiography-on-film techniques, specification of film types, methods of measuring focal spots, measuring X-ray kilovoltage, specifications for film viewers, IQI designs, IQI acceptable values and classes, personnel qualification – all of which are now mandatory in most European countries.

## 2. Digital radiography

Almost all film radiographs are interpreted by placing the film on a suitable illuminated screen and viewing the film image by eye. A trained, skilled film reader with good knowledge of the specimen (material, method of manufacture, characteristic flaws, etc.) can recognise any image detail on the film,

can determine its dimensions, and with the aid of acceptance codes can assess the specimen's suitability for service. It has always been tempting, ever since the availability of closed-circuit television cameras and computers, to see whether a camera producing digital data could replace the human eye, the argument being that the eye can get tired and miss seeing images of flaws, whereas the camera has no fatigue problems. Also, digital data from the camera can be stored on an optical disc, the capacity of a 300 mm disc being several thousand radiographs, and this would eliminate the need for long-term film storage which has always been a difficult problem. Instead of using a CCTV camera, it is possible and more satisfactory to record the image on the film by scanning the image with a very small light spot, usually from a laser, and convert the readings into digital data for storage on disc or tape; there is also obvious potential for digital image enhancement and automated interpretation, as well as for storage. The size of the scanning spot must be related to the resolution of the image on the radiograph and the grey scale of the data storage system must be related to the density range on the radiograph. 8 bits corresponds to 256 grey levels and 12 bits to 4096 levels. To cover a film of density range 0-4 on 0.01 density steps would require 400 grey levels, but a typical weld radiograph is unlikely to have a density range of more than two – 1.5-3.5, which is only 200 grey levels. The transmitted light intensity through the film, coupled with the spot area, must not be such as to introduce any signal-to-noise limitations and this is the reason for using a laser light spot. Low voltage X-radiographs with a very small total unsharpness require a scanning spot in the range 30-50 micrometres diameter while a 100 micrometre spot should be adequate for most radiographs. Density variations down to 0.01 should be separable. A pixel size of 50 micrometres corresponds to 6000 pixels across a 300 mm film image. Halving the resolution reduces the data volume by a factor of four .

For re-examination of the images on a monitor screen it is essential that the image has the same image quality as the original radiograph and this can today be done with 2000-4000 raster line equipments. With a 3000 line monitor the line separation, which corresponds to the introduced image unsharpness would then be 0.1 mm, which corresponds roughly to the effective unsharpness of a high quality X-radiograph. Conventional 625-line TV is not therefore generally adequate. Such potential limitations can of course be minimised by covering a small area of film. Also, of course, on many radiographic applications the maximum image resolution is not required across the whole of the image.

Once the film image is available in digital data, there is potential to attempt to devise automated image interpretation using suitable computer programmes, and there have been several research papers [6, 7] on this topic,

but so far as I am aware, only a few successful applications in industry [8]. Image enhancement, including noise suppression is certainly possible and the contrast sensitivity of a television/digitisation system can almost match the performance of the eye in terms of contrast sensitivity, but the trained eye is a very powerful interpreter of image shapes. If one considers a simple, fine (tight) crack in a weld, this can propagate in almost any direction: if it happens to be in line with the X-ray beam it is seen on the film as a sharp narrow black line; if the plane of the crack is angled to the X-ray beam the image is broadened, is much fainter, and may disappear entirely, or disappear and reappear as the crack twists. Programmes to recognize such images from digital data, have, so far as I know, proved impossible.

In some materials such as ceramics, porosity is the critical flaw, and here, as one has a standard shape of flaw, automated flaw recognition systems may be possible.

## 2.1. Standards for film digitisation

Film digitisation systems can be classified by the size of the sampling area, whether the original data is taken from radiographic film or from an imaging plate (see Sec. 3).

Digitisation can be point-by-point with a laser scanner, or line-by-line with a CCD scanner, or area scanning with a television camera. The latter is the simplest, with no moving parts and can be adapted to produce a logarithmic output signal so that the digitised grey scale value is proportional to film density. However, because of light scatter problems only a small density range of the film can be covered at one time.

Both CEN [9] and ASTM [10] are producing standards on film digitisation which are broadly similar and are in final draft form. ASTM and Germany (DIN) use a standard reference radiograph [11] containing various images of spatial resolution specimens, in order to evaluate the parameters of the film digitisation system [12], but the precise contents of the image of this

TABLE 1. Minimum density range of the radiographic digitisation system with a minimum density contrast sensitivity.

Parameter	Class DS	Class DB	Class DA
Density range*	0.5 to 4.5	0.5 to 4.0	0.5 to 3.5
Digital resolution (bit)	$\geq 12$	$\geq 10$	$\geq 10$
Density contrast sensitivity DD	$\leq 0.02$	$\leq 0.02$	$\leq 0.02$

\* This density range may be split into separated working ranges.

TABLE 2. Minimum spatial resolution of film digitisation system.

Energy keV	Class DS		Class DA		Class DA	
	Pixel size [ $\mu\text{m}$ ]	MTF 20% [lp/mm]	Pixel size [ $\mu\text{m}$ ]	MTF 20% [lp/mm]	Pixel size [ $\mu\text{m}$ ]	MTF 20% [lp/mm]
$\leq 100$	15	16.7	50	5	70	3.6
$> 100$ to 200	30	8.3	70	3.6	85	3
$> 200$ to 450	60	4.2	85	3	100	2.5
Se-75, Ir-192	100	2.5	125	2	150	1.7
Co-60, 1 MeV	200	1.25	250	1	250	1

reference film is still under discussion. In the CEN draft standard three classes of digitisation system are proposed, DA, DB, DS. Tables 1 and 2 show the proposed values and these are then related to the two classes of radiography described in EN-444 and EN-1435 as shown in Table 3.

TABLE 3. Minimum digitisation class depending on the radiographic testing classes A and B, if radiographs are taken on the basis of EN-444, EN-1435.

Wall thickness [mm] steel	Class DS	Class DB	Class DA
$< 5$	B	A	–
$\geq 5$	B	B	A

### 3. Non-film systems

Radiography-on-film is expensive and obviously film can only be used once, and for many years plates coated with some radiation-sensitive layer have been proposed as substitute for film. In recent years there have been considerable developments in this field.

40 years ago there was Xeroradiography – the X-ray equivalent of xerography used in document copiers. A thin coating of amorphous selenium on an aluminium plate will hold an electrostatic charge on its surface when it is kept in a dark place such as a cassette. An X-ray beam through a specimen will partially discharge the surface according to the radiation dose absorbed, leaving an ‘electrostatic’ image which can be revealed by dusting the surface with a white powder. The image can be viewed, recorded, and the plate

cleaned for further use. Xeroradiographic images were of remarkably high quality, but the process has fallen into complete disuse, so far as I know, due to lack of commercial exploitation. Consistently good selenium coatings of the correct thickness were very difficult to produce.

However, a whole range of flat panel imaging plates is now marketed.

Agfa market a 'Radview Direct Radiography' system which directly captures the X-ray image and converts it into digital data. The sensitive plate consists of a layer of amorphous selenium 500 micrometres thick, coated on a thin film transistor (TFT).

With a bias voltage applied across the detector structure, incident X-rays generate electron-hole pairs in the selenium layer and the charges are collected by individual storage capacitors associated with each detector element, for read-out by customised electronics within the array. The result is a 14-bit digital image which can be viewed immediately on a video monitor. The plates can be up to  $35 \times 43$  cm with an element size of  $130 \times 130$  microns and a similar element pitch, so the effective image unsharpness due to the plate structure is 0.13 mm.

Agfa and Fuji both market computed radiography systems which use a photostimulable storage phosphor (BaFBr), which is also available as flat plates up to  $35 \times 43$  cm. After exposure in a standard film cassette the plate is removed and inserted into a scanner using a laser spot to scan the plate surface. The laser light spot releases trapped electrons, causing visible light to be emitted and this light is converted into digital data to be viewed on a monitor. The laser spot is 87 microns in diameter and scan pitch can be between 100 and 250 microns on a 12-bit output. After examination, the image can be erased and the plate re-used. The plates have a very wide exposure latitude, a very high speed in terms of the dose required to produce an image, and a noise level (S/N ratio) of about the same as medium-speed radiographic film. The resolution is therefore limited compared with slow fine-grain radiographic films, but the high speed means that these plates can be used with lowoutput microfocus X-ray equipment, to produce an enlarged image by projective magnification. A third type of imaging plate uses a silicon layer bonded on to a phosphor layer, usually of CsI or  $Gd_2O_2S$ . Such plates can be ten times faster than conventional film and have a noise level equivalent to medium-speed film. Vaessen [13] has examined several of these plate systems and some of his measurements are shown in Fig. 2. This data is for 200 kV X-rays and a geometric unsharpness of 0.04 mm, so that the total effective unsharpness is mostly due to the characteristics of the plates. With the Si/CsI plate the unsharpness is probably about 0.3 mm and will dominate the total unsharpness.

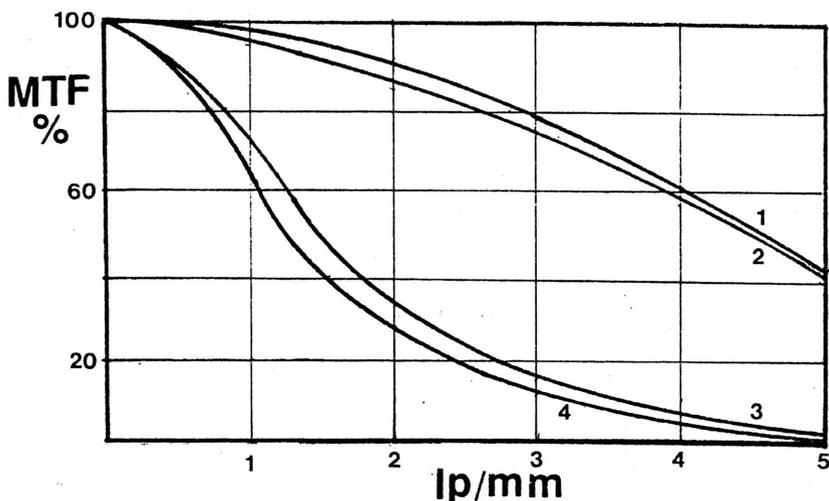


FIGURE 2. Modulation transfer function (MTF) curves for film and detector plates, according to Aessen (Ref. [13]). 1 – Selenium layer, direct; 2 – Film, 100 kV; 3 – Silicon layer with gadolinium oxysulphide phosphor; 4 – Silicon layer with caesium sulphide phosphor.

It is worth noting that the S/N ratio depends on the exposure given to the plate and becomes a significant parameter in image quality in addition to unsharpness. Vaessen defines noise-equivalent-aperture (NEA) as the aperture corresponding to 20% MTF value and it follows that  $\infty$  (determined for film) is proportional to NEA. Some of Vaessen’s calculations are shown in Table 4.

TABLE 4. Digital detectors and film [8].

Detector material	Converter thickness [μm]	Pixel size [μm]	NEA [μm]	S/N ratio
Se	500	139	154	135
BaFBr	500	100	286	51
Si+Csi	150	143	400	93
Si+GOS	500	126	364	67
Film (D4)	150	–	–	100
Film (D2)	–	–	–	156

The film data is based on 200 kV X-rays with a 8 mm Cu filter and a 20 mm steel specimen. A filter of 100 μm Pb and 0.5 mm Fe was placed on top of the detectors.

CEN Committee TC-138 has initiated a project on 'Industrial Computed Radiography with Phosphor Imaging Plates' which is attempting to classify systems into six classes based on minimum and maximum S/N ratio values ( $S/N - \log e G/\sigma_D$ ), speed, and unsharpness. The different classes of imaging plate are then related to the two classes of radiography detailed in EN-444 and EN-1435 for different X- and gamma-ray sources. The work is not yet complete and the Standards are still in the draft stage [14].

#### 4. Radioscopy

It has always been the desire to have instant real-time X-ray images of good quality. Simple fluoroscopy was extended in the 1950s by X-ray image intensifiers, and then in the 1960s by closed-circuit television systems (CCTV) viewing a fluorescent screen. CCTV cameras have developed rapidly since the first Vidicons and Isocons, both in sensitivity and reliability, and better quality fluorescent screens are also now available. Modern radiosopic equipment therefore uses either:

- A CCTV camera taking the image direct from a fluorescent screen, via suitable optics is shown in Fig. 3.
- An X-ray image intensifier tube, which has a suitable conversion screen built-in, coupled to a CCTV camera is shown in Fig. 4.
- A scanning system in which a linear array of detectors scans across the X-ray beam transmitted through the specimen.

There are also hybrid designs.

All three methods produce digital data which is stored, processed and represented on a television monitor screen. The basic technical problem to be overcome is that the light output of a conventional fluorescent screen is very low. Method A uses an 'open' fluorescent screen which can be changed in size or material, but requires a very sensitive CCTV camera, whereas Method B can use a less sensitive camera, but the primary conversion screen is inside the image intensifier tube.

In all these methods there are new sources of image unsharpness to be taken into account – the primary screen, the television camera scanning raster, the pixel digitisation size, the monitor line raster, (all to be combined with the geometric unsharpness) and it is likely that the total unsharpness of the system is between 0.3 and 0.8 mm; that is, much greater than with a typical film system.

Image contrast is no problem with digitised image data; contrast, both local and overall, is easily controlled.

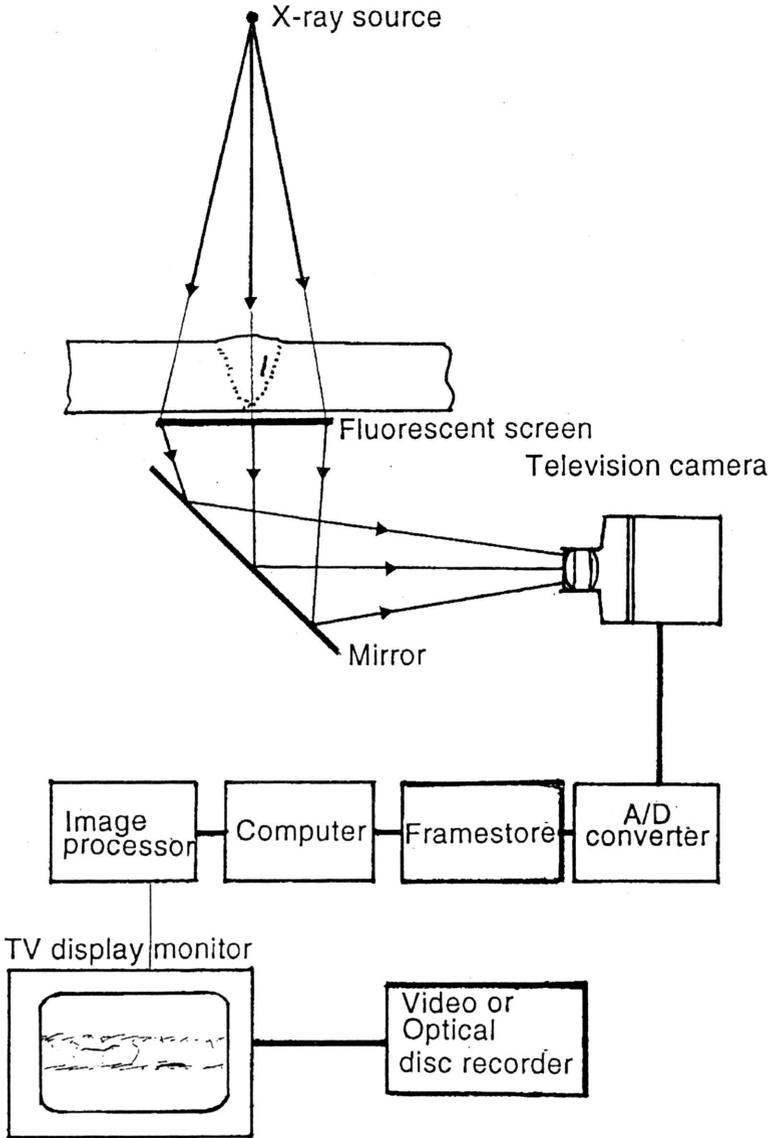


FIGURE 3. Radioscopy: typical block diagram of "open" screen equipment.



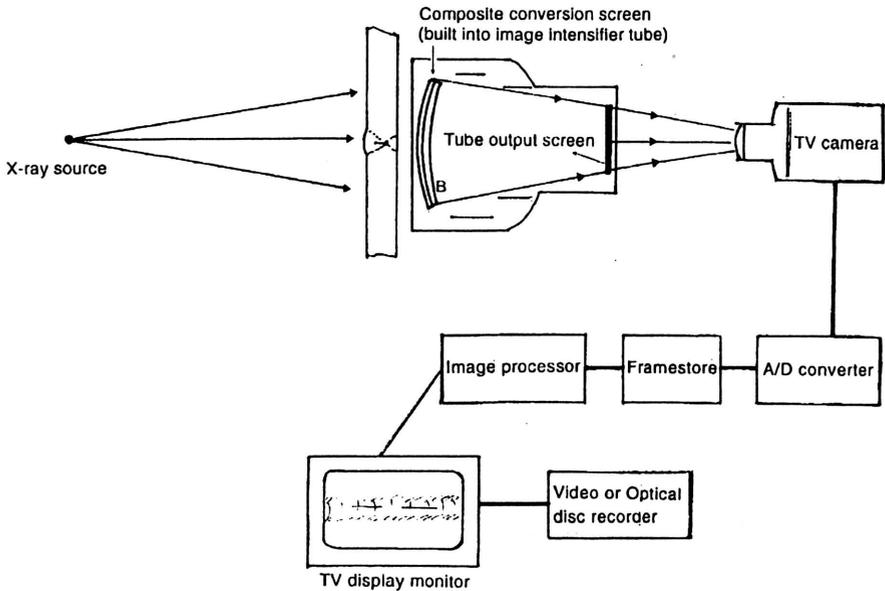


FIGURE 4. Radioscopy: typical block diagram of equipment using an X-ray image intensifier tube.

On the specifics of equipment, I am probably out-of-date, as developments in CCTV cameras and conversion screens have been very rapid in recent years, but the essential principles of image quality are the same with all equipments.

Image sharpness depends on the source of the largest single image unsharpness through the system, which is usually the primary conversion screen. Figure 5 shows MTF curves for the individual components of a radioscopic system, together with the total MTF of the whole system.

By using a microfocus or minifocus X-ray tube, both of which have been developed to be reliable industrial equipments, the image can be enlarged by projective magnification without significant increase in geometric unsharpness. This has the effect of reducing the effective screen unsharpness ( $U_s$ ) to  $U_s/M$  where  $M$  is the magnification factor. There are also 'image sharpening' programmes which can be applied to the digital data.

Image noise can be a serious problem with radioscopic systems because of the very high amplification through the television/image intensifier chain. CCTV cameras normally produce an image from the number of quanta received during one television frame (1/30 s) but at the digital stage with static images it is easily possible to integrate the data from several frames and the noise is reduced by  $F^{1/2}$  where  $F$  is the number of frames integrated. To

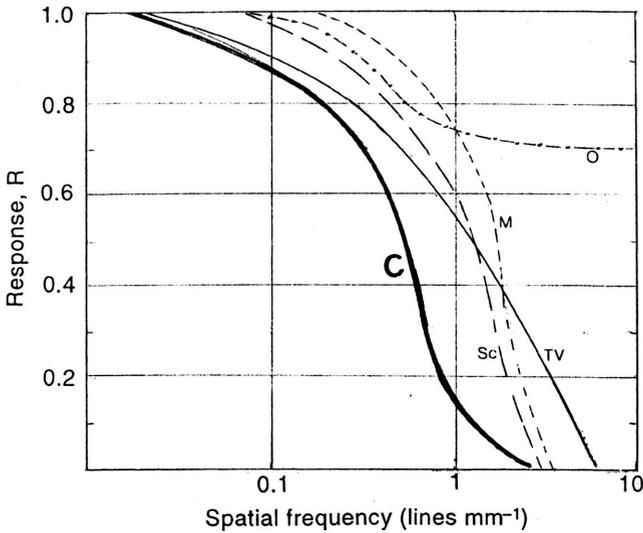


FIGURE 5. MTF curves for components of a typical radioscopic equipment: O – optic, TV – television camera, M – display monitor, Sc – primary conversion screen, C – combined curve for overall performance of complete equipment.

integrate the quanta from 100 frames requires only four seconds. CEN has produced a large Standard on Radioscopic Testing [15] and has proposed three equipment classes – Table 5.

TABLE 5. Minimum requirements for radioscopic detector systems [15].

	System Classes		
	SC1	SC2	SC3
Inherent detector unsharpness U better than	0.4 mm	0.5 mm	0.6 mm

There are additional requirements in respect of distortion and homogeneity.

The inherent unsharpness of the system is measured from the image of a sharp step in the specimen under specified conditions. The Standard specifies two system classes for different applications, corresponding to the two classes of radiography-on-film described in EN-444 and EN-1435, and the performance of the equipment is specified by two parameters – the wire IQI number and the image of a duplex wire IQI (discernibility of wire pairs); the latter criterion is a measure of image unsharpness and the former largely of image contrast.

Image processing of radioscopic images is now standard practice and a four-stage process is common:

1. frame integration to reduce quantum noise,
2. thickness equalisation (reduction of brightness range),
3. contrast enhancement, local or overall,
4. image 'crispning' – a form of image sharpening.

Radioscopic methods are now well-established in industry, particularly for castings inspection.

One very important development in radioscopy has been that with the enormous increase in computer data storage capacity, it is now possible to rotate and translate a specimen and store the image at each position of movement. With suitable programmes, 3-D and tomographic images are obtainable from radioscopic equipment [16].

A major market for radioscopic equipment is in the security inspection of luggage at airports, etc. Baggage is moved on a travelling belt system between an X-ray source and a detector screen. Equipments have been built capable of examining the largest luggage; also equipments using a linac source of X-rays or a very intense gamma-ray source and very large detector screens have been used for the examination of large vehicles such as container lorries. These equipments are sometimes coupled to 'sniffing' devices to detect drugs, alcohol and refugees.

## 5. Tomography

In 1979 Hounsfield invented the process known as computed tomography (CT) or computed axial tomography (CAT), in which an X-ray image of a thin slice through a specimen is obtained by means of suitable computer programmes applied to absorption data from several positions and angles through the specimen. These are the well-known 'brain scan' and 'body scan' medical equipments. Nearly all the basic work was done in the medical field, but there has been a slow application to industrial problems. Early equipments used a single element detector with parallel geometry, then a linear array with a divergent X-ray beam was used, and this is the usual modern design of industrial tomographic equipment [17]. The use of area detectors such as flat-panel plates is also possible. In industrial applications the X-ray or gamma-ray sources and the radiation detectors are usually fixed and the specimen is moved between them, Fig. 6.

There has been much development of the theory of image reconstruction, to improve the images, to produce images from incomplete data, to reduce the image construction time, and also development of multi-element detectors to

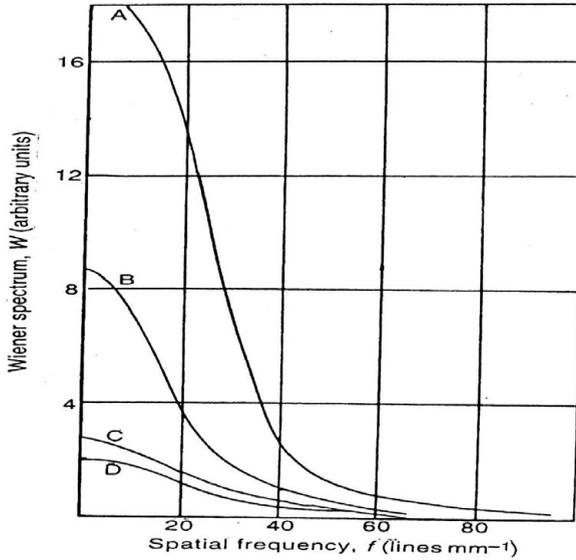


FIGURE 6. Wiener spectra (experimental) for different radiographic films, exposed with 400 kV. X-rays, A – very fast film, B – medium speed film, C – fine grain film, D – very fine grain film.

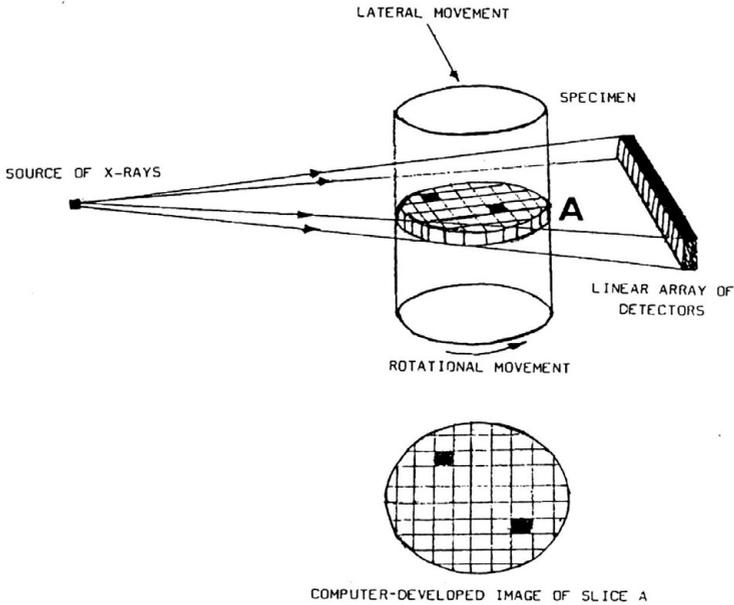


FIGURE 7. Sketch of set-up for computerised tomography using a linear array of detectors.

reduce scan-times, but industrial take-up of CT has been quite slow outside research laboratories.

Scan-times of the order of minutes and image-reconstruction-times of similar length are typical.

Microtomography of very small specimens is also possible [18]: portable equipment using gamma-rays has been built for on-site use [19], and as in other methods of radiography factors such as geometric unsharpness, detector size, pixel raster, etc., control the attainable image quality.

Image resolution on medical equipment is of the order 100-500  $\mu\text{m}$ , because of the need to minimise dosage to the patient and depends on specimen diameter, whereas industrial equipment has reached 10  $\mu\text{m}$  on a small object using microfocus equipment and projective magnification [18], although 100  $\mu\text{m}$  is probably a more realistic value.

It is probable that 3-D imaging will become more commonplace in CT applications as a result of using area detectors [16]. Committees of both ASTM and CEN are investigating procedures for CT.

## 6. Other methods

In a survey of this sort, within a limited number of words, it is not possible to cover all developments. I have not discussed neutron radiography, which does not seem to have progressed much in the past 20 years.

Phase contrast radiography and tomography [20] are mentioned in the literature as possible new methods and there are such methods as the use of back-scatter radiation, laminography, proton radiography, radiometric methods, Digiray tubes, on which references occasionally appear in the literature, have found only very limited application.

Given available inspection time, the use of slow fine-grain radiographic film with appropriate technique parameters is still the bench-mark technique with which all other methods are compared.

There is still a regrettable lack of knowledge of the performance of radiological methods in detecting real defects in materials, such as cracks.

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