Handbook of X-ray Imaging
Physics and Technology
Paolo Russo

Industrial Radiography

Publication details
Uwe Zscherpel, Uwe Ewert
Published online on: 14 Dec 2017

How to cite :- Uwe Zscherpel, Uwe Ewert. 14 Dec 2017, Industrial Radiography from: Handbook of X-ray Imaging, Physics and Technology CRC Press
Accessed on: 05 Dec 2023

PLEASE SCROLL DOWN FOR DOCUMENT

Full terms and conditions of use: https://www.routledgehandbooks.com/legal-notices/terms

This Document PDF may be used for research, teaching and private study purposes. Any substantial or systematic reproductions, re-distribution, re-selling, loan or sub-licensing, systematic supply or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The publisher shall not be liable for an loss, actions, claims, proceedings, demand or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.
Industrial Radiography

Uwe Zscherpel and Uwe Ewert

CONTENTS

30.1 Introduction.................................................................................................................. 595
30.2 Industrial X-ray Films (NDT Films)............................................................................... 596
30.3 Image Quality in Industrial Radiography..................................................................... 599
  30.3.1 Contrast................................................................................................................. 600
  30.3.2 Noise and Granularity ......................................................................................... 600
  30.3.3 Unsharpness........................................................................................................ 601
30.4 Visibility of Flaws and Image Quality Indicators.......................................................... 601
30.5 Image Quality Indicators and Standards.................................................................... 603
  30.5.1 Image Quality Indicators (IQI)............................................................................ 603
  30.5.2 Standards on DIR................................................................................................ 605
30.6 Digital Industrial Radiology (DIR).............................................................................. 605
  30.6.1 NDT Film Digitization........................................................................................ 605
  30.6.2 Image Processing................................................................................................ 606
  30.6.3 Computed Radiography and Its Industrial Application ........................................ 606
    30.6.3.1 Correlation of SNR to Gray Values for Computed Radiography ....................... 607
    30.6.3.2 Weld Inspection by CR.................................................................................... 608
    30.6.3.3 Measurement of Pipe Wall Thickness for Evaluation of Corrosion, Erosion, and Deposits ................................................................. 609
  30.6.4 Industrial Radiography with Digital Detector Arrays (DDA). ............................ 609
    30.6.4.1 Detector Types and Working Principles.......................................................... 609
    30.6.4.2 Line Detectors................................................................................................ 610
    30.6.4.3 Application of DDAs: High Contrast Sensitivity Technique with DDAs .......... 611
    30.6.4.4 Application Limits of DDA: DDA Calibration and Achievable SNR .................. 611
    30.6.4.5 Testing of Heat Exchangers............................................................................ 612
    30.6.4.6 Mechanized X-ray Inspection of Welds............................................................ 613
    30.6.4.7 Automated Evaluation of Digital X-ray Images: Serial Inspection in Automotive Industry .......................................................... 614
References.............................................................................................................................. 616

30.1 Introduction

Industrial radiography is typically applied for the volumetric inspection of industrial products and installations (Halmshaw 1995; Bossi et al. 2002; Czchos 2013). W.C. Roentgen himself did the first radiographs of this kind in 1896, by imaging soldered tin plates and his hunting rifle (Glasser 1939) (see also Section II, Chapter 17 of this book for an historical introduction to Roentgen’s discovery; the original plate made by Röntgen of his shotgun is reproduced as Figure XXVI in the historical gallery, in the middle of this book). The basic setup consists of a radiation source in front of the object to inspect an area detector behind the object to capture the penetrated shadow image of the object under investigation. The classical detector is an X-ray film. New electronic area detectors are gradually substituting film. The radiation source can be an X-ray tube, a gamma source, a linear accelerator, or a particle accelerator, generating, for example, neutron, proton, or other charged particle radiation. Objects of all possible materials and thicknesses can be inspected, provided the right radiation source and energy is selected. There exist practical limitations to the upper material thickness, for example, 0.5 m penetration length in steel or 2 m in concrete (at an X-ray radiation energy of 12 MeV).

Industrial radiography is based on the discovery of X-rays by W.C. Roentgen in 1895, the discovery of gamma radiation by H. Becquerel in 1896, and the extraction of Radium sources by P. and M. Curie in 1898. After the development of high-vacuum X-ray tubes with energies up to 100 keV in 1913, radiological techniques were introduced into industrial practice. Over the last decades, tremendous progress in hardware has occurred, such as the development of radioscopic systems with X-ray image intensifiers, micro-focus X-ray tubes, and digital detector systems. This progress was accompanied by an enormous increase in computing capabilities, which made the introduction of digital techniques possible, such as digital image processing and enhancement, automated defect recognition, data reconstruction, and three-dimensional computed tomography applications (see Chapter 45). Nowadays,
the increased capabilities of digital detection systems, such as storage phosphor imaging plates (CR—Computed Radiography, see Chapter 12) and flat panel detectors (DDA—Digital Detector Arrays), indicate a new era in industrial radiography.

### 30.2 Industrial X-ray Films (NDT Films)

At the beginning of radiography, the same kind of X-ray films were used for medical and industrial applications. However, soon after the end of the 1940s, and its wide use of industrial radiography (also called non-destructive testing—NDT) for inspection of welds on vessels and tanks (military usage) or bridges and piping (civilian usage), the development of films splits into two branches: medical films with high light sensitivity using scintillator screens for lowest dose sensitivity for only one radiation-sensitive object (the human) and industrial films using lead screens for high image sharpness, but with very low sensitivity compared to medical films. The compensation of the lower sensitivity by higher dose is not a problem, because industrial objects are not harmed by any X-ray dose. The industrial usage of metal screens with its intensification of the optical density in contact with films at the same dose level was discovered in the 1920s in the US and, after World War II (WWII), it was also implemented in Europe (Schnitger 1984). The basic idea was to expose the film not by light, as in the medical case using scintillator screens typically based on Gd_2O_2S, which converts the X-ray radiation into light exposing the film, but to use heavy metal screens like thin Pb layers inside the film cassette. The Pb screens generate photo electrons and, in close contact to the film emulsion, these electrons expose film emulsions. The metallic screens can be made very thin (10–20 µm) and, together with very fine grained films, the inner unsharpness of such an industrial film system can be below 20 µm for energies below 100 keV. Therefore, the production of industrial X-ray film with film grains below 1 µm and a high silver content started worldwide after WWII and, therefore, the properties of medical X-ray films and the industrial X-ray films, as used today, are really different. These differences are not very well known, because most literature describes the medical film version only. Even the classical book on industrial radiography by Halmshaw (1995) does not discuss this in detail. An overview on the properties of industrial X-ray films is presented here, based on the ongoing international film system evaluation, which is done at the Federal Institute for Materials Research and Testing (BAM) since the 1960s.

In Figure 30.1, a medical film (AGFA film type F8 specified for industrial applications in combination with RCF fluorescence screens) for very high sensitivity, but low contrast inspections, for example for reinforcement detection in concrete, is compared with a fast NDT film (Fujifilm IX100, which is not de-sensitized for light). Typically, NDT films are today de-sensitized for light for easier darkroom handling, because only electrons expose the film in NDT. The characteristic film response to the exposed radiation is the optical film density, D, after film development. The optical density of the film is a logarithmic measure of the light transmission of an exposed and developed film. The applied optical film density for medical films is typically between D = 1 to 2. Industrial applications for non-destructive testing (NDT) use general exposure dose values which are 10- to 1000-times higher. The resulting NDT image quality is characterized by higher sharpness and contrast sensitivity. Industrial radiographic films usually contain a higher silver content, which allows for obtaining a higher optical density (blackening). NDT films are applied for density values between 2 and 4.5. Special high brightness viewing stations are required. Medical viewing equipment is not sufficient. Industrial films have been manufactured for more than 40 years on a polyester or PET base (100–150 µm thick), which is often of blue tint for better flaw visibility on a yellowish

![Characteristic film curves of industrial films](image-url)
NDT films have a linear response between exposure and optical density, which is much more clearly visible in Figure 30.2.

Here films are used in combination with lead screens and exposed with 220 kV X-ray radiation pre-filtered with 8 mm Cu, the standard exposure conditions of ISO 11699-1. In ISO 11699-1 also the NDT film system classes are defined for industrial application: classes C1 to C6. The AGFA F8 film shown in Figure 30.1 is a special (medical) film (too fast and too low silver content for NDT) and does not fulfill the requirements of ISO 11699-1 for industrial film systems with metallic screens (lead screens typically with 27 or 10 µm thickness).

NDT film systems are classified corresponding to the standards ISO 11699, EN 584 (replaced by ISO 11699 in 2012), JIS K 7627, and ASTM E 1815. The classification requires the user to select the film type and the developer, as well as the certified developer temperature, and immersion time, to obtain conformity with the standards.

NDT film emulsions have smaller grains than medical or photographic emulsions adapted to light exposure. In Figure 30.3, the two typical grain shapes of NDT films are shown: classical cubic grains (used by AGFA and FOMA (see FOMA NDT (2012) systems) and the “T-Grains” (used by KODAK and CARESTREAM, see Droin and Roussilhe 2006). T-Grains are generated when some of the AgBr (cubic crystallites) is replaced by AgI (hexagonal symmetry).

For industrial applications, the grain shape makes little differences, but the grain size itself determines the sensitivity (“speed”) of the film emulsion. The name D2 of AGFA results from an average grain size of 200 nm, the D7 film has a grain size of about 700 nm. Opposite to a film exposure with light, where several light photons are needed to activate a grain (so called “seed” in the latent image before film development), in NDT, one X-ray photon, which generates several photo electrons in the metal screen, can activate several grains in a film emulsion. Therefore, such effects, like the Schwartzschild effect, and the decay of seeds at very low exposures, cannot happen for NDT film systems. The optical density versus dose curves are almost linear, as shown in Figure 30.2. However, the energy of the electrons and, in consequence, their mean free path in the emulsion depends on the X-ray energy used for film exposure. In Figure 30.4 (Ewert and Zscherpel 2013), the influence of the X-ray energy and also material thickness (causing beam hardening) on the edge unsharpness, measured with the method of Klasens (1947/48), is shown.

X-ray radiation below 100 keV can generate very sharp images, because the free path of the exposing electrons is short.
With higher energy, this inner film unsharpness is increased. The fluctuations of the optical density in the film, the noise called “granularity” in ISO 11699-1, is a result of the quantum mottle of the impinging X-rays and the free electron path lengths of the electrons generated by the Pb screen in the film emulsion. The visible film noise after development is NOT due to the film grain distribution, as discussed for photographic film emulsions, where this noise is called “graininess.” As a result, the visible film noise of an Ir-192 exposure and a low-energy X-ray exposure look totally different. The industrial film systems are meanwhile optimized, so that a human observer is not able to recognize any noise in a normal film exposure. Magnifying glasses or suitable film digitization will reveal this noise.

The grain size of industrial films does not contribute to the film noise, but determines the sensitivity of the film system, as shown in Figure 30.2. This is a result of the generation of the “seeds” in the latent image by electrons, which occurs only at the surface of the grains. Having large grains, the electrons can generate seeds in a latent image with a large amount of silver after development. With smaller grains, more electrons are needed to generate a latent image with the same silver content after development. The optical film density after development is proportional to the number of seeds and to the number of electrons, emitted from the screens, and, therefore, also to the exposure dose. NDT systems are linear, with a deviation of only a few percent in the working range shown in Figure 30.2. ISO 11699-1 defines the procedure how to measure the film granularity. This is performed by a scanning microscope using a round aperture with a diameter of 100 μm in a film plane, imaging both emulsions, measuring the transmitted light intensity, and converting this value to the diffuse optical density of the film sample under investigation. This aperture size is determined by the resolution of a human observer at 30 cm distance without a magnifying glass. Statistically independent neighbored aperture areas on the film are scanned, and the standard deviation of these noisy aperture values in diffuse optical densities is calculated as the granularity value (for more details see ISO 11699-1). According to system theory in a quantum limited system (X-rays), the noise is the square root of the number of quanta (Poisson noise). The optical density is the signal of the film, which is proportional to the exposure dose (see Figure 30.2), thus the number of detected X-ray quanta. Therefore, it is expected that the film granularity should be proportional to the square root of the optical density, since the film granularity is caused by the quantum statistics of the X-ray radiation. Measurements of the granularity depending on the film density on different NDT film systems are shown in Figure 30.5 (Jadeed 2015).

The relationship of the granularity to the square root of the optical density is disturbed by a quadratic term, which alters from negative to positive with an increasing film system number. C3 film systems were measured as nearly linear. This effect changes with a decreasing gradient (the gradient is defined as a slope of the H&D plot at a given density) at $D = 2$, with increasing film system class and ISO speed.

Finally, ISO 11699-1 defines the gradient over granularity ratio (at an optical density of $D = 2$ over fog and base) as the figure of merit of the NDT film system, which can be converted to the signal-to-noise ratio (SNR) measured for the film system.

Figure 30.6 shows a good correlation of measurements of the gradient over granularity ratio versus square root of exposure dose for NDT film systems analyzed from 2002 until 2013 at BAM Berlin. This demonstrates that a NDT film system can be considered as a quantum detector. This is valid for all classified film systems of all NDT film manufacturers, and even for all the mixed systems measured in the time period. A mixed system is a film of manufacturer “A” developed in chemistry of manufacturer “B.” These mixed systems are just shifted along the median line in Figure 30.6. This median line has a slope of 73.3 mGy$^{-0.5}$, which is based on the efficiency of the used metallic screens of 27 μm Pb in direct contact to the film emulsions (front and back side) and 220 kV X-ray radiation with an 8 mm Cu pre-filter at...
Tube port according to ISO 11699-1. Since these parameters are fixed for all film systems shown in Figure 30.6 (ISO 11699-1), all investigated film systems are moving along the median line and are in between the shown error limits of ±7%. The film system class limits according to ISO 11699-1 are marked as well as the median line and the achieved uncertainty of ±7%. The consequences of Figure 30.6 are presented in Table 30.1. From the minimum gradient/granularity ratios at $D = 2$ above fog and base requested by the standard ISO 11699-1 for the different film system classes, this ratio is directly correlated to a minimum exposure dose to reach this ratio and a maximum ISO speed of the film system, as the inverse number of the exposure dose (in Gray) for $D = 2$ above fog and base. Of course, in practice, the films are best in the middle of each film system band, as shown by the measurement values in Figure 30.6. Therefore, $S_{\text{average}}$ are typical ISO speeds for commercially available film system classes.

The footnotes in Table 30.1 describe the conversion of the minimum gradient/granularity values of the film system classes measured according to ISO 11699-1 and the minimum normalized signal/noise ratio $\text{SNR}_{\text{opt}}$ of a digitized film image, with an optical density of $D = 2$ above fog and base. According to the system theory for a linear quantum detector (film), the normalized $\text{SNR}_{\text{opt}}$ is proportional to the square root of the optical density and an exposure dose proportional signal. So, the furthest right column of Table 30.1 can be used when digitized film images are evaluated for the achieved image quality and compared to other digital images from detectors like DDAs or imaging plates.

### 30.3 Image Quality in Industrial Radiography

The image quality is that characteristic of a radiographic image which determines the degree of visible detail (Czichos 2013). It

<table>
<thead>
<tr>
<th>ISO 11699-1 Minimum</th>
<th>Gradient over Granularity Ratio, $G_2/\sigma$, at $D = 2$ over Fog and Base</th>
<th>Minimum Exposure Dose with $K = (G_2/\sigma)/(73.3)^2$ in mGy</th>
<th>Maximum ISO Speed $S$ According to Figure 30.6, $S = 1/(K \text{ in GY})$</th>
<th>Average ISO Speed, $S_{\text{average}}$, of NDT Film Systems</th>
<th>Minimum Normalized Signal to Noise Ratio, $\text{SNR}_{\text{opt}}$, after Film Digitization</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISO 11699-1 Film System Class</td>
<td>$K$ According to Figure 30.6</td>
<td>$60$</td>
<td>$50$</td>
<td>$260$</td>
<td></td>
</tr>
<tr>
<td>C1</td>
<td>300</td>
<td>16.8</td>
<td>100</td>
<td>80</td>
<td>200</td>
</tr>
<tr>
<td>C2</td>
<td>230</td>
<td>9.8</td>
<td>170</td>
<td>125</td>
<td>155</td>
</tr>
<tr>
<td>C3</td>
<td>180</td>
<td>6.0</td>
<td>240</td>
<td>200</td>
<td>130</td>
</tr>
<tr>
<td>C4</td>
<td>150</td>
<td>4.2</td>
<td>370</td>
<td>320</td>
<td>105</td>
</tr>
<tr>
<td>C5</td>
<td>120</td>
<td>2.7</td>
<td>525</td>
<td>500</td>
<td>85</td>
</tr>
<tr>
<td>C6</td>
<td>100</td>
<td>1.9</td>
<td>525</td>
<td>500</td>
<td>85</td>
</tr>
</tbody>
</table>

* This value is calculated as $\text{SNR}_{\text{opt}} = 2 \log(e) (G_2/\sigma) at D = 2$ above fog and base. The correction factor $\log(e)$ results from the linear film response and the log definition of the gradient. An additional factor of 2 has to be considered, because the film granularity is measured by a circular aperture of 100 μm diameter (see ISO 11699-1). The SNR normalization in ISO 17636-2 (film replacement by DDA and CR) and ISO 16371-1 (film replacement by CR) is related to a basic spatial resolution of 88.6 μm, which corresponds to a circular aperture size with a diameter of 200 μm.
is influenced by a large variety of influencing factors originating in the inspected object (material, thickness), the radiation source (radiation quality), the imaging system (detector properties), geometry (focal spot size, source-to-object distance, object-to-detector distance), and image noise (photon statistics and fixed pattern noise of detectors). Image quality is typically measured by image quality indicators (IQI), objects with a known geometry, which are placed on the surface of the investigated specimen and analyzed in the obtained radiographic image. It can also be predicted from essential parameters as signal-to-noise ratio (SNR), effective attenuation coefficient, \( \mu_{\text{eff}} \), and basic spatial resolution, \( SR_{\mu,\text{map}} \), of the image (Ewert et al. 2012b).

The major problem in industrial radiography is the image degradation by scattered radiation, generated by Compton scattering inside the penetrated object. This radiation can be much larger than the imaging primary radiation, depending on the material, the penetrated thicknesses, and used X-ray energies.

### 30.3.1 Contrast

The generation of a radiographic image can be explained in terms of a simple step wedge object (see Figure 30.7).

The radiation intensity or optical density difference seen between two thicknesses at a given detector intensity, \( I \) (signal), or optical density in an object on a radiograph represents the absolute radiographic contrast in the image:

\[
C_I = I_1 - I_2
\]

(30.1)

with the intensities \( I_1 \) and \( I_2 \) after penetrating a material of thickness \( d_1 \) and \( d_2 \), respectively. Introducing \( I_p = I_p \) as a reference primary intensity, a linear relation follows between the absolute contrast, \( \Delta I \), and the thickness difference from the exponential attenuation law, \( I_p = I_0 e^{-\mu d} \) (approximation for small thickness differences, \( \Delta d \ll d \)):

\[
\Delta I = I_p \mu \Delta d
\]

(30.2)

For the interpretation of radiographs, the relative contrast, \( C_r \), is important, which describes the imaging of an indication:

\[
C_r = \frac{\Delta I}{I}
\]

(30.3)

with \( I = I_1 + I_p \) giving the total intensity. For small thickness differences, it follows that:

\[
C_r = \frac{I_p \mu \Delta d}{I_1 + I_p} = \frac{\mu}{1 + k} \Delta d = C_{\text{rel}} \Delta d
\]

(30.4)

with the scatter ratio \( k = I_k/I_p \) and the relative specific contrast \( C_{\text{rel}} = \mu/(1 + k) \). Hence, the relative contrast and the relative specific contrast increase with the attenuation coefficient, \( \mu \), but decrease with increasing scattering ratio and increasing material thickness. The term \( \mu(1 + k) \) is also named \( \mu_{\text{eff}} \). The scatter ratio increases with the material thickness. It is about 0.1-times the thickness of steel (in mm) for X-ray inspection with film (if the film is in contact with the object). The influence of the X-ray energy is low in comparison to the dependence on the material and material thickness for the scatter ratio. Gamma sources and linear accelerators generate radiation with higher equivalent energies, which produces lower scatter ratios than X-ray tubes and, therefore, the relative specific contrast is higher in comparison to X-ray radiography at high material thickness.

### 30.3.2 Noise and Granularity

The perception of any indication depends on its area, the contrast-to-noise ratio (CNR), and image unsharpness. The image noise is measured quantitatively as the standard deviation of the mean value of the intensity or density in a projected area of constant object thickness. Density fluctuations are described as granularity of film systems. The visual impression is noisy. The term noise is used dominantly in digital radiography (see also Section I, Chapters 14 and 15 of this book, for an introduction to the theory of image quality in X-ray imaging).

Different noise sources have to be considered in digital radiography, which have their origin in the following reasons (Ewert and Zscherpel 2013):

- **EXPOSURE CONDITIONS:** Photon noise, depending on exposure dose (e.g., mA s or GBq min). *This is the main factor!* CNR increases with higher exposure dose.

  The maximum achievable CNR at a given radiation energy is limited by:

  - **DETECTOR:** Structural noise of DDAs and Imaging Plates also called fixed pattern noise (due to variations in pixel to pixel response and inhomogeneities in the detection layer).
  - **OBJECT:**
    - Crystalline structure of material (e.g., nickel based steel, mottling).
    - Surface roughness of test object.

  The first two noise sources can be influenced by the exposure conditions and detector selection. The achieved CNR of images

\[
\]
Industrial Radiography

depends on the exposure dose (low dose application). The CNR increases with the square root of mA (minutes) or GBq (minutes), due to the improved X-ray photon quantum statistics. The structure noise of films and imaging plates depends on its manufacturing process, and can be influenced basically by the selection of the specific detector type (e.g., fine- or coarse-grained film). Film development and IP scanner properties contribute also to the final noise figure. The structure noise of detectors and all noise sources depending on the object properties determine the maximum achievable CNR and limit; therefore, the image quality independently on the exposure dose (high dose application) (Ewert et al. 2012b). Only with Digital Detector Arrays, the structure noise (due to different properties of the detector elements) can be corrected by a calibration procedure, since the characteristic of each element can be measured quite accurately (Ewert et al. 2010a).

30.3.3 Unsharpness

The sharpness of the outline of an image is directly affected by the geometrical unsharpness generated by the source size, the source-to-object and the source-to-detector distances (SOD, SDD), and the inherent unsharpness, $u_r$, of the detector.

The blurring of an edge image due to a finite focal spot size, $S$, is defined as geometrical unsharpness, $u_g$ (Figure 30.8, left)

$$u_g = \frac{(SDD - SOD)}{SOD} \cdot S = (M - 1) \cdot S \quad (30.5)$$

with magnification factor, $M$, and source size, $S$, according to Figure 30.8 (right)

$$M = \frac{SDD}{SOD} \quad (30.6)$$

Additionally, the detector system contributes to the system unsharpness. Due to the properties of the detector, an additional edge blurring is observed. It can be drawn back, for example, to the use of intensifying screens and to the scattering of photons or electrons in the detector layers. This contribution is called inherent unsharpness, $u_r$.

The total unsharpness, $u_{T,\text{image}}$, observed in a radiographic image (neglecting the effect of motion during exposure), is the convolution of the geometrical and the inherent unsharpness contributions normalized to magnification, and can be approximated by

$$u_{T,\text{image}} = \frac{1}{M} \sqrt{u_r^2 + u_g^2} \quad (30.7)$$

The optimal geometry for taking radiographs with minimum effective unsharpness ($u_{T,\text{image}}$) can be determined if the inherent and geometrical unsharpness are chosen equivalent. From this condition, the optimal magnification, $M_{\text{opt}}$, for the best spatial resolution is

$$M_{\text{opt}} = 1 + (u_r/S)^2 \quad (30.8)$$

As long as the projection, $d' = Md$, of an object of size $d$ is larger than the total unsharpness, the contrast of the indication is not decreased, and follows Equation 30.2. If the unsharpness exceeds $d'$, a decrease of the indication contrast is observed (compare Figure 30.9).

30.4 Visibility of Flaws and Image Quality Indicators

Figure 30.10 illustrates the effect of signal, contrast, and noise on the detectability of a notch in a radiographic image (Ewert and Zscherpel 2013). The visibility of fine flaws and IQIs for human observers depends on the normalized contrast to noise ratio, CNR$_n$ per material thickness difference, and its lateral shape in the two-dimensional radiograph (Ewert et al. 2012b).

CNR$_n$ is the normalized CNR, which is the ratio of the CNR to the effective pixel size (basic spatial resolution of the image, $SR_b^{\text{image}}$) of digital images. For small flaws and IQIs, CNR can be approximated by the product of the relative specific contrast, $C_{\text{rel}} = \mu_{\text{eff}}$ (effective linear attenuation coefficient), the signal to noise ratio, SNR, and the thickness change, $\Delta d$, generating the contrast:

$$\text{CNR} = \mu_{\text{eff}} \cdot \text{SNR} \cdot \Delta d \quad (30.9)$$
The basic spatial resolution (effective pixel size in an image), $SR_b^{\text{image}}$, can be measured in different ways. The NDT community mostly uses the duplex wire method due to its simplicity (ISO 19232-5 and ASTM E 2002). The measurement with the duplex wire IQI provides a total image unsharpness value ($\mu_T$) in micrometers. The basic spatial resolution of a digital image, $SR_b^{\text{image}}$, is defined by:

$$SR_b^{\text{image}} = \frac{\mu_T^{\text{image}}}{2} \quad (30.10)$$

Figure 30.11 illustrates the contributing parameters to the specific normalized Contrast-to-Noise Ratio, $CNR_N^{\text{specific}}$, thus, $CNR_N$ per wall thickness change, $\Delta d$ (Ewert and Zscherpel 2013). The visibility of flaws of constant lateral size depends on three essential parameters, as given in the following equation, which is an approximation for IQIs and small flaws:

$$CNR_N^{\text{specific}} = \mu_{\text{eff}} \cdot \frac{SNR}{SR_b^{\text{image}}} \quad (30.11)$$

This is an essential context for digital radiography (Ewert et al. 2012b).

The visibility of flaws and IQIs for human operators is calculated as a product of $CNR_N$ and the square root of the lateral projected area of flaws and IQIs (Rose 1946, 1948; Ewert et al. 2012b). The human operator can recognize (percept) larger flaws at a lower $CNR$ and, therefore, also at a lower SNR (see Figure 30.12).

This is a result of the quantum limited sensitivity of the human eye or any other light detector, as discovered first time by Rose (1946, 1948). Almost all contrast IQIs change their diameter proportional to their thickness, this applies to wire IQIs (ISO 19232-1, ASTM E 747) as well as to the hole diameters in plate and step hole IQIs (ASTM E 1025, ISO 19232-2).
Industrial Radiography

603

The visibility (“perception threshold of human eye”) of holes in IQIs depends on the normalized CNR$_n$ (= CNR/σ) and the diameter of the IQI holes (square root of hole area). An X-ray image of a 20 mm thick steel plate with different drilled flat bottom holes was generated with a digital detector (simulation). The depth of the flat bottom holes and, consequently, the contrast was doubled from the lower line of holes to the upper one. The noise was almost constant in the whole image. The diameter was always doubled, starting from the left column to the right one. The diameter of the 1T hole corresponds to 0.25 mm (5 pixels).

If the ratio of IQI thickness to hole diameter is fixed (see standards ASTM E 1025, ASTM E 1742, ISO 19232-2), the visibility (depending on a constant human perception threshold; PT) of plate hole or step hole IQIs depends on the square root of CNR$_n$. In ASTM E 747 and E 1742 and related standards, the equivalent penetrameter sensitivity (EPS) is used to describe the visible contrast sensitivity of a human operator as a percentage of the penetrated wall thickness (Ewert et al. 2012b).

Note: a sensitivity of 2%, for example, means that a hole in a thin IQI plate of 2% thickness of the material to inspect with a hole diameter of 2-times the plate thickness (2T) is just visible in the radiograph. This is described as 2-2T sensitivity or 2% EPS in the standards.

The equivalent IQI sensitivity (EPS as a percentage) can be calculated for a given material thickness, $t_{\text{plate}}$, from the essential parameters (see Figure 30.11 and Equation 30.12), as follows (see also ASTM E 746 and E 1025):

$$ EPS = \frac{PT}{t_{\text{plate}}} \sqrt{\frac{SR_{\text{image}}}{\mu_{\text{eff}} \cdot SNR}}$$  \hspace{1cm} (30.12)

with $PT \approx 2\text{–}100\%$ for IT holes, determined from practical trials for clear visibility of holes on a monitor. This formula applies if the basic spatial resolution is much smaller than the wire or hole diameter of the IQI to be visualized. The smaller the EPS value achieved, the smaller flaws and IQIs can be visualized. A small EPS value means the contrast sensitivity is high. All three of the essential parameters in Equation 30.12 determine the image quality. Improving one parameter can compensate for reduction of others. For instance, the increase of tube voltage increases the SNR, but reduces the $\mu_{\text{eff}}$. If SNR increases faster than $\mu_{\text{eff}}$ decreases, the total EPS improves (Ewert et al. 2010a).

30.5 Image Quality Indicators and Standards

30.5.1 Image Quality Indicators (IQI)

Image quality indicators are standardized devices comprising a series of elements of graded dimensions, which enable a measure of the image quality to be obtained. IQIs are usually used for every radiograph to check the adequacy of the used radiographic technique. The elements of IQI are commonly wires and steps or plates with holes. IQI, together with their usage, are described in detail in the ISO standards ISO 19232 part 1–5 and the American standards ASTM E 747, E 1025, and E 2002.

Wire type IQI consist of wires that are arranged by diameter and have all the same length (Figure 30.13a). The wire material is chosen to match the material of the investigated object. It measures the thickness resolution of the radiographic technique.

The European step hole IQI system is based on a series of steps of different thickness, $d$, and holes of diameter equal to the step thickness (Figure 30.13b). The material is chosen to match the material of the investigated object. The image quality value is given by the number of the smallest hole, which is visible in the radiograph.

The American plate hole IQI (ASTM E 1025 and E 1742) consists of a small rectangular or circular piece of metal, usually containing several holes, the diameters of which are related to the thickness of the plate. The ASTM penetrameter contains three holes of diameters 1T, 2T, and 4T, where T is the thickness of the plate. The material is again chosen to match the material of the investigated object. The IQI gives the equivalent penetrameter sensitivity (EPS) in terms of contrast resolution, which is a measure for the minimal resolvable thickness difference, together with the minimal resolvable detail influenced by the total unsharpness (see also Figure 30.11).
Duplex wire indicators (Figure 30.13c) are used when it is necessary to evaluate and measure the total image sharpness (spatial resolution or basic spatial resolution) separately from contrast sensitivity measurements. Every element consists of two wires of a certain diameter, with equal spacing between the wires. High attenuating material is chosen for the wires, such as tungsten and platinum. The wire diameter of the largest element without identifying a separation between the image of the two wires (“dip < 20%,” see ISO 17636-2 or ASTM E 2002) is taken as the basic spatial resolution and, according to Equation 30.10, the total image sharpness is calculated.

**TABLE 30.2**
Overview on Digital Industrial Radiology Standards and New Drafts of CEN, ISO, ASME, and ASTM without Standards on Computed Tomography (Status of 2016)

<table>
<thead>
<tr>
<th>Standard</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN 13068</td>
<td>Radioscopy</td>
</tr>
<tr>
<td>EN 14096, ISO 14096</td>
<td>Film Digitization, 2 parts</td>
</tr>
<tr>
<td><em>Goes after revision to ISO 16371</em></td>
<td>Part 2: General principles</td>
</tr>
<tr>
<td>ISO 10893-7:2010</td>
<td>Steel tubes—NDT of welds with DDA and CR</td>
</tr>
<tr>
<td>EN 16407:2014</td>
<td>Corrosion and wall thickness measurement, Practice with film, CR and DDA for tangential technique (part 1) and double wall inspection (part 2)</td>
</tr>
<tr>
<td>ASME (BPVC, S.V, Article 2)</td>
<td>Radiography and Radioscopy with Film, CR, DDA, ...</td>
</tr>
<tr>
<td><em>Revision on the way and nearly finished</em></td>
<td>Characterization (E 2597M-14), Guide (E 2736-10), Practice (E 2698-10), Long-Term Stability (E 2737-10)</td>
</tr>
<tr>
<td>ASTM DDA (2010)</td>
<td>Standard Practice for Digital Imaging and Communication in Non-destructive Evaluation (DICONDE), data formats for CT, CR, DR, film digitization, ultrasonics, visual testing, ...</td>
</tr>
<tr>
<td><em>Revision on-going</em></td>
<td>Digital reference images electronic catalogs for Al, investment steel castings, titanium and steel castings, Magnesium, Mg, and Al dye castings are already available, the conversion of all 13 ASTM film catalogs to electronic reference images is on-going</td>
</tr>
<tr>
<td>ASTM DICONDE (2010)</td>
<td></td>
</tr>
<tr>
<td>E 2339-10, E 2663-08, E 2699-10, E 2738-10, E 2767-10</td>
<td></td>
</tr>
<tr>
<td>ASTM Reference Catalogs</td>
<td></td>
</tr>
<tr>
<td>E 2422-05, E 2660-10, E 2669-10, E 2669-10, E 2868-13, E 2869-13, E 2973-15</td>
<td></td>
</tr>
</tbody>
</table>
TABLE 30.3
Application Areas of Digital Industrial Radiology (DIR)

<table>
<thead>
<tr>
<th>Digital Industrial Radiology</th>
<th>Film Replacement</th>
<th>New Industrial Areas Partly Standardized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standardized applications</td>
<td>Non-standard applications</td>
<td>Serial part inspection</td>
</tr>
<tr>
<td>Welding</td>
<td>Buildings</td>
<td>Automated defect recognition (ADR)</td>
</tr>
<tr>
<td>Casting</td>
<td>Bridges</td>
<td>Completeness test</td>
</tr>
<tr>
<td>Wall thickness, corrosion, erosion</td>
<td>Plastics, composites</td>
<td>Dimensional check</td>
</tr>
<tr>
<td>Electronics</td>
<td>Food, tires, wood, …</td>
<td></td>
</tr>
</tbody>
</table>

30.5.2 Standards on DIR

Table 30.2 provides an overview about the most important standards on digital industrial radiology (DIR). In 2005, Europe and the USA published the first complete sets of CR standards. Especially, at ASTM the standardization has been pushed ahead over the last 10 years. The next set of standards of DIR with DDAs was published in 2010. Today the revision of the CR standards is on-going. At CEN and ISO, a common standard was published in 2013 (ISO 17636), which substituted EN 1435 (only film as detector) for radiographic weld inspection. The new ISO 17636 considers film (part I) and CR and DDAs (part II) as film replacement for weld inspection.

30.6 Digital Industrial Radiology (DIR)

Users of digital industrial radiology (Czichos 2013), who are interested to move from classical film radiography to digital industrial radiology (DIR), should know which particular application field they want to enter. Basically, there exist unregulated and regulated areas (standards, guidelines, and others). Table 30.3 describes the four basic application areas.

Before new methods and detectors will be described, the advantages of traditional film radiography should be summarized. One of the major advantages of X-ray film radiography is its practicability. Important NDT film properties are:

- They are dust- and waterproof packed.
- They consist of flexible and break-proof material.
- The storage period after film development is >50 years (expected shelf life >500 years).
- The readability is independent of technological development (e.g., independent of data format).

30.6.1 NDT Film Digitization

Film digitization systems can be classified by the sampling technology (see Table 30.4).

For example, digitization with a laser scanner proceeds as shown in Figure 30.14.

The film passes a scanning slit. A laser beam (wavelength about 630 nm, red) with a fixed diameter (e.g., 50 µm) scans the film. The diffuse transmitted light through the film is integrated by a light collection tube and registered by a photo multiplier tube (PMT) on top of the collection tube (not shown in Figure 30.14). During the scan, the rotation polygon mirror deflects the laser beam and moves the spot along a horizontal line in the scanning slit. The film is advanced with a constant speed. The resulting current of the photo multiplier is proportional to the light intensity behind the film. After logarithmic amplification, a digitization yields gray values that are proportional to the optical density of the film.

The essential difference to other digitization principles in Table 30.4 is the reversed optical alignment. The laser scanner illuminates with focused light and measures the diffuse light intensity behind the film. All other methods illuminate the whole area of the film with diffuse light (the film is illuminated with a diffuser) and measure the light intensity that passes the film in one direction at each spot (camera objective or human eye in classical film inspection).

Complementary metal-oxide-semiconductor (CMOS) cameras, which generate a logarithmic output signal relative to the input light intensity, are also available. In this case, the digitized gray values will be proportional to the film density, and do not follow the linear light intensity characteristics as digitized with charge-coupled device (CCD) chips, which will need a logarithmic conversion to obtain gray values proportional to the optical film density.

The standard ISO EN 14096 defines the qualification procedure (part 1) and the minimum requirements (part 2) for film digitizers in NDT. NDT applications employ X-ray energies of 10 to 15,000 keV. The standards require a pixel size (basic spatial resolution) of 15 to 250 µm, depending on the energy. This corresponds to a required spatial resolution of 16.7 lp/mm (line pairs...
per millimeter) for energies <100 keV and, for example, 1 lp/mm for 1300 keV.

On the basis of the image quality of film radiography, the standard requires three quality classes: DA, DB, and DS. The user may select the testing class based on the needs of the inspection:

- DS: the enhanced technique, which performs the digitization with an insignificant reduction of signal-to-noise-ratio and spatial resolution; application field: digital archiving of films (digital storage).
- DB: the enhanced technique, which permits some reduction of image quality; application field: digital analysis of films; films have to be archived.
- DA: the basic technique, which permits some reduction of image quality and further reduced spatial resolution; application field: digital analysis of films; films have to be archived.

### 30.6.2 Image Processing

A digital image is physically not more than a data file in a computer system linked to a program capable of displaying its contents on a screen or printout, dot by dot. That means it consists of an array of individual image points. These are called picture elements (pixels). The pixels represent in practice small rectangles (squares) showing a certain color and brightness on the output device (printer or display).

The image resolution depends on the number of pixels within a given area; the more the better (see Figure 30.15).

Radiography commonly deals only with gray-level images, which represent the detected X-ray exposure at a given point in the image. The numerical values of any pixels within an image can be subjected to various kinds of calculations. Each pixel is characterized by a gray (intensity) value. The most trivial step is to adjust brightness and contrast when displaying the image. However, this does not allow one to overcome the lower luminance of monitors compared to commercial film viewers. The human eye can only distinguish between some 80 shades of gray (at a given adaptation, equivalent to 6–7 bits of information), and a digital image may contain up to 65,536 gray levels (i.e., 16 bits). Thus, the contrast and brightness adjustments are essential to select the range of interest, so the 80 shades of gray on the display have to be selected very carefully when inspecting images with 16 bit gray values! The gamma transformation alters the linearity of the transfer from the original digital values listed in the image file to the digital driving levels used for image display on the screen, taking into account the brightness sensitive perception of human eyes.

Multiple-point calculations take advantage from relationships between adjacent pixels of the image (matrix operations). They are based on a variety of so-called convolution filter algorithms that are supposed to extract the desired features from the total image information. They may eliminate unwanted large, background intensity variations from changes in penetrated wall thickness, or noise masking other image details. Typical filters are described in Table 30.5. Processing of radiographic images is discussed together with filter recipes, in different textbooks (Lindley 1991; Gonzalez and Woods 2002; Osterloh and Zscherpel 2012).

#### 30.6.3 Computed Radiography and its Industrial Application

Storage phosphor imaging plates (IP) are image media for film-less radiography (Ewert et al. 1995). The technique is also called computed radiography (CR) (see also Section I, Chapter 12 of this book, for a description of CR). IPs are routinely used in medicine and biomedical autoradiography. Different systems are available for NDT applications. Novel applications in addition to film radiography emerge, taking advantage of the higher sensitivity (shorter exposure time) and the digital image processing, as well as the capability to analyze digital radiographs with affordable computer systems. A set of standards was published first in 2005 in Europe and the USA.

![FIGURE 30.15 Radiographic image of a test weld BAM5](image_url)

**TABLE 30.5 Typical Image Processing Filters**

<table>
<thead>
<tr>
<th>Digital Filter</th>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-pass filter</td>
<td>Increases the signal-to-noise ratio</td>
<td>Reduces the spatial resolution</td>
</tr>
<tr>
<td>High-pass filter</td>
<td>Increases the contrast of fine details in relation to intensity changes in a wide range, mostly used in NDT for reduction of the displayed dynamic range</td>
<td>Reduces the signal-to-noise ratio</td>
</tr>
<tr>
<td>Median filter</td>
<td>Increases the signal-to-noise ratio, removes single peaks and outliers (single white or black pixels such as “salt and pepper” distortions), does not smooth edges</td>
<td>Reduces the spatial resolution</td>
</tr>
<tr>
<td>Edge filter</td>
<td>Enhances edges or extracts edges to lines</td>
<td>Increases the noise</td>
</tr>
</tbody>
</table>

which defines the classification and practice of CR systems for NDT applications (CR-Standards: EN 14784:2005).

IPs are handled nearly in the same way as radiographic films. After exposure, they are read by a laser scanner producing a digital image instead of being developed like a film (see Figure 30.16).

Any remaining latent image can be erased with a bright light source so that the same IP can be recycled up to 1000 times. An IP consists of a flexible polymer support which is coated with the sensitive layer, which is sealed with a thin transparent protective layer. The sensitive layer of the most common systems consists of BaFBr doped with Eu$^{2+}$. X-ray or gamma-ray quanta result in an avalanche of charge carriers, such as electrons and holes in the crystal lattice (Ewert et al. 1995).

These charge carriers may be trapped at impurity sites, such as electrons at a halogen vacancy (F-center) or holes at an interstitial Br$^-$ molecule (H-center). Red laser light (600–700 nm) excites electrons trapped in a Br$^-$ vacancy (FBr-center) to a higher state from which they may tunnel and recombine with a nearby trapped hole. Transfer of the recombination energy excites a nearby located Eu$^{2+}$ ion. Upon return to its ground state, this Eu$^{2+}$ ion emits a blue photon (390 nm). This process is described as photostimulated luminescence (PSL).

The advantages of IP technology are:

- High linearity with radiation dose.
- High dynamic range, up to $10^5$.
- Higher sensitivity than NDT film systems using lead screens.
- Reusable for 1000 cycles.
- No chemical darkroom processing.
- Capability for direct image processing.

The disadvantages are:

- Limited spatial resolution of fast IPs.
- High sensitivity in the low-energy range; therefore, very sensitive to scattered radiation.
- IP surface must be handled very carefully, if 1000 times re-useage should be achieved.

The available systems of storage phosphor imaging plates and corresponding laser scanners cover radiation dose differences of up to $10^{4}$. This feature reduces the number of exposures for objects with a high wall thickness difference. It also compensates partly for incorrectly calculated exposure conditions. The number of so-called test exposures is reduced. The IP reader is typically separated from the inspection site. CR is based on flexible IPs (Ewert et al. 1995). High-definition CR systems can provide a basic spatial resolution of better than 40 μm. This is sufficient for weld and casting inspection of small components at lower X-ray voltages, as well as large components. The optimum X-ray voltage for CR is different from film radiography (Ewert et al. 2010b). For coarse grained imaging plates, the tube voltage should be reduced by about 20% in comparison to film radiography. Details of the procedure are described in ISO 17636-2:2013.

### 30.6.3.1 Correlation of SNR to Gray Values for Computed Radiography

Monitoring the image quality by measurement of the SNR in production radiographs is difficult, because these radiographs may be distorted by shading and noise contributions from the inspected objects. This reduces typically the measured SNR values. NDT operators can monitor the gray values in radiographs easier than SNR values. Imaging plate–CR scanner systems provide digital radiographs with a strict correlation between linear gray value response and SNR at a fixed parameter setting (pre-supposing the gray values are yielded linear to the exposure dose). This is widely independent of the radiation energy and the inspected material, but it depends on the IP type, the scanner, and its settings. Figure 30.17 shows the correlation of SNR as a function of the gray value at different mA and kV settings and for different test objects (step wedges) and exposure times.

An ideal radiation detector without inherent fixed pattern noise acquires digital images which depend on the quantum statistic of the photons (Poisson statistics) only (Ewert et al. 2012b).
That means the detector noise increases with the square root of the detector signal (gray value). So, the ideal detector converts all photons which interact with the detector into gray values (GV) (counter principle) proportional to the number of detected photons:

\[ SNR_{\text{ref}} \propto \frac{GV_{\text{phot}}}{P_{\text{m}}}, \]

(30.13)

The production process of the IPs (coating of the storage phosphor on a plastic carrier) results in slight thickness variations of the storage phosphor layer. This generates a variation of sensitivity of this layer, depending on the IP location, the so-called fixed pattern noise. This fixed pattern noise is an inherent property of any storage phosphor imaging plate, which limits the maximum achievable SNR in the image. It is called SNR_{\text{max}}, and increases linearly with the number of converted (counted) photons. The SNR of a detector with fixed pattern noise increases as follows with the dose (Ewert et al. 2010b):

\[ SNR = \frac{GV_{\text{measured}}}{\sqrt{(GV_{\text{measured}}/SNR_{\text{max}})^2 + GV_{\text{measured}}/Eff^2}}, \]

(30.14)

The gray value efficiency (Eff_{ip}) in computed radiography depends on the X-ray efficiency of the used imaging plate and the scanner parameters as, for example, gain, scan speed, and other internal conversion settings. The Eff_{ip} is for instance directly proportional to the scanner gain, if the scanner provides dose proportional digital images. Figure 30.17 shows the measured SNR values as a function of the measured gray values for two different imaging plates (UR-1 and ST-VI of Fujifilm) scanned with the DynamIx HR scanner (of Fujifilm).

This fixed correlation between gray value and SNR in a scanned IP image independent on the radiation energy is a special property of CR, and is comparable with the change of different film system classes, see Figure 30.6. CR allows a much higher dynamic range than films. This range is limited by the IP structure noise, causing a maximum achievable SNR. This limits the contrast sensitivity of CR systems, see Equation 30.11. CR systems have been produced for NDT applications for about 20 years, and the image quality of the IPs (achievable SNR_{\text{max}}) is still improving with each new IP generation.

30.6.3.2 Weld Inspection by CR

The inspection of welds and castings is traditionally performed by film radiography. Since the optical photography has been almost completely converted from film to digital photography, the trend is also visible in X-ray radiography. Nevertheless, the conversion rate from film to digital radiography applications is slow. First developments have been reported for application of computed radiography for weld inspection of pipelines. Figure 30.18 shows a typical application.

CR with imaging plates permits faster inspection if the requirements are taken from ASME BPVC (Section V, Appendix 2). This standard allows higher unsharpness and less contrast sensitivity than the ISO 17636, class B, which is difficult to achieve with sensitive imaging plates.
30.6.3.3 Measurement of Pipe Wall Thickness for Evaluation of Corrosion, Erosion, and Deposits

A typical application of the CR technology is the radiographic corrosion inspection in the chemical industry (Zschepel et al. 2006). Figures 30.19 and 30.20 present typical examples of thermally insulated pipelines and the related radiographic measurement procedure.

The insulation is covered with an aluminum envelope. The radiographic inspection can be performed without removing the insulation. This is a considerable advantage relative to the other known methods. Radiographic pipe inspection for corrosion and wall thickness measurement is a major NDT technique for predictive maintenance. CR is also more and more applied for inspection of valves and armatures for functionality check and deposit search. See EN 16407 for more details on this inspection technique.

30.6.4 Industrial Radiography with Digital Detector Arrays (DDA)

30.6.4.1 Detector Types and Working Principles

Two types of DDAs (also called flat panel detectors) are available on the market. The first design (see Figure 30.21) is based on a photodiode matrix connected to thin-film transistors (TFT) (Ewert and Zscherpel 2013).
These components are manufactured on amorphous silicon, and they are resistant against ionizing radiation. Alternatively to the amorphous silicon panels, CMOS arrays can also be applied. The photodiodes are charged by light, which is generated by a scintillator converting the incoming X- or gamma rays. This scintillator can be a polycrystalline layer that causes some additional unsharpness by light scattering or a directed crystalline system, which acts like a face plate with lower unsharpness, due to inhibited light scattering (see Figure 30.22).

The next generation (second type of DDAs) of flat panels is based on a photoconductor like amorphous selenium (Ewert and Zscherpel 2013), silicon, or CdTe (EU project, 2005) on a multi-microelectrode plate, which is also read out by TFTs (see Figure 30.23b) or CMOS arrays. Direct converting photodiode systems (Figure 30.23a) are not used in NDT, due to their low quantum efficiency using the silicon base material as absorber (only usefully for energies below 20 keV).

DDAs are suitable for in-house and in-field applications. In-field applications are characterized by harsh environmental conditions in some areas, which imply the risk of hardware damage and restrict the mobile application of DDAs. First DDAs are on the market, which are protected against moisture and mechanical load.

### 30.6.4.2 Line Detectors

The classical concept of NDT with line detectors is based on a fixed radiation source, moving objects and a fixed line camera.
This is the typical concept for baggage, car, and truck inspection. Line detectors are available with a pixel resolution of 0.25 to 5 mm. The most common principle is the combination of scintillator and photodiodes. The scintillator is selected in accordance with the energy range.

### 30.6.4.3 Application of DDAs: High Contrast Sensitivity Technique with DDAs

DDAs can provide a significantly better contrast sensitivity than films and imaging plates (Ewert and Zscherpel 2005; Ewert et al. 2005a,b, 2008; Bavendiek et al. 2006). This is known as High Contrast Sensitivity (HCS) technique (Bavendiek et al. 2006). The signal response of the different DDA detector elements can be corrected by a calibration procedure, since the characteristic of each element can be measured quite accurately.

Figure 30.24 shows the effect of SNR increase (equivalent to CNR increase) on the visibility of fine flaw indications (Ewert et al. 2008). The digitized NDT film (film system C1) provides a SNR of 265 in the base material region at magnification of 1. The DDA image was acquired with a SNR of about 1500 using a magnification of 3.5. It shows significantly more flaw indications than the digitized film image. The increase of the SNR is the key parameter for the increase of the contrast sensitivity corresponding to Figure 30.11 and Equation 30.12.

### 30.6.4.4 Application Limits of DDA: DDA Calibration and Achievable SNR

DDAs contain millions of pixels. They do have differences in conversion gain (X-ray dosage to gray value) and also offset values (gray value higher than zero even if no radiation is detected) between the pixels, caused by the detector electronics. Even pixels can be dead or over responding, these are called “bad pixels.” For optimum DDA performance these raw data of the DDA are not useful and need to be corrected by an additional procedure called “detector calibration.” This detector calibration is typical for all types of DDAs, it is not used in film radiography or CR. Line scanners used for film or image plate scanning use similar approaches to equalize the scanner response along the scanning line (scan line calibration). A “dark image” (image acquisition without X-ray dosage) averaged by N frames for noise reduction in the final dark image and a “flat field image” without any object, but with a typical material plate and thickness penetrated by X-rays, are needed for detector calibration. The SNR in the acquired DDA increases with the number of averaged frames, see Figure 30.25.

Figure 30.25 shows the application of the different calibration procedures for the Hamamatsu detector C7942 (CMOS, CsI scintillator, 50 µm pixel size). The typical calibration uses a white and dark image to compensate for the dark signal...
and equalize the sensitivity of the different detector elements (SNR_{N,max} of 550 in Figure 30.25). It is important to acquire the dark and the flat field image within a considerably longer acquisition time than for measurement to avoid introducing noise by the calibration procedure. At least a 2-times longer integration for dark and flat field image than for measurement of the digital radiographs should be sufficient. A plate of 30 mm Al was positioned near the target of the X-ray tube to calibrate for Al inspection. It was observed that some structural noise remains, due to the non-linear response of the detector elements. A non-linear 4-point calibration using three flat field images at different dose values was used to consider the non-linearity of the detector elements. The structural noise could be decreased and the SNR_N limit was increased to 810. This limit seems to be influenced by the inspected material. Fine mottling effects also act as a kind of structural noise. Positioning the calibration material in front of the detector added structural noise from the Al structure. The max obtainable SNR_N with the 4-point calibration was reduced down to 725. In summary, the detector calibration carried out by the user of the DDA system limits the application range and the CNR of the DDA. This is an essential difference for DDA applications in comparison to films or CR with IPs, where these limits are set by the manufacturer and cannot be influenced by the user!

### 30.6.4.5 Testing of Heat Exchangers

The radiographic inspection of tube-to-tube sheet welds using Ir 192 isotope as radiation source and NDT film as detector is state of the art since decades (see Figure 30.26).

![FIGURE 30.24 Better detail visibility of flaws by increased SNR of the DDA image in comparison to a digitized film image of the weld sample “BAM 5.”](image)

![FIGURE 30.25 SNR limitations due to the effect of different calibration procedures. The non-linear 4-point calibration with an Al filter in front of the X-ray tube reduces best the structural noise of the detector.](image)
For this application, the vacupaced films have to be punched light-tight to pass the radio isotope source through the film caused by the one-sided accessibility of the tube sheet. Special wall thickness compensators are used to account for wall thickness changes in penetrating direction across the inspected weld regions. The sensitivity of this testing method is limited by the properties of the radiation source. Since heat exchangers are shipped worldwide over country boarders, NDT teams from different countries need to be involved. Nowadays, the testing with radio isotopes becomes more and more complicated, due to tough radiation protection regulations and transport limitations.

A direct converting detector, based on CdTe semiconductors, was redesigned in 2004 (DIC100TH, 2006). Together with a rod anode X-ray tube (X-ray tube MCTS 130A-0.6, 2007), a handsome unit was designed with four detector tiles arranged around the rod anode, which passes though the detector plane (see Figure 30.27).

The handling of this inspection unit, as well as the computer-based image acquisition, sped up this radiographic (RT) inspection considerably. All problems with film chemistry, any consumables, and isotope transportation are avoided now. Within a very short time period, the investment into the expensive inspection equipment is amortized. In this way, the single-sided access for weld inspection was realized as an X-ray endoscope. The controlled area could be reduced considerably, because the unit provides best image quality in the range of 70 to 90 kV X-ray voltage compared with Ir 192 requirements (max. energy about 650 keV) as used before.

30.6.4.6 Mechanized X-ray Inspection of Welds

High-resolution detectors have been introduced for weld inspection (Casagrande et al. 2000; Ewert et al. 2012a). Figure 30.28 shows a mechanized X-ray inspection system, which is based

![FIGURE 30.26 Classic design for inspection of tube-to-tube sheet welds. The gamma source is shifted from the radiation protection container into the tube through an X-ray film with a central hole. The radiation penetrates the tube-to-tube sheet weld and exposes the film, which is placed between the radiation protection container and tube sheet. (Reproduced with permission from Zscherpel, U. et al. 2012. X-ray endoscopy for inspection of tube to tube sheet welds in heat exchangers. 18th World Conference on NDT. April 16–20, Durban, South Africa. http://www.ndt.net/article/wcndt2012/papers/335_wcndtfinal00335.pdf.)](image1)

![FIGURE 30.27 Digital X-ray endoscope for inspection of tube-to-tube sheet welds. A rod anode X-ray tube (X-ray tube MCTS 130A-0.6) and four DDA tails (DIC100TH) are integrated for fast digital inspection (Zscherpel et al. 2012). The image quality is improved in comparison to the system with Ir-192 and film. Furthermore, a reduced controlled area is required and the inspection speed is about 10 times faster than for the classical inspection.](image2)
on an X-ray tube, a manipulation system, and a detector (Ewert et al. 2016).

New applications take advantage of photon counting technology to improve the sensitivity (Walter et al. 2016). The image information is processed in the computer and a cross-section is reconstructed. Specialized tomographic routines were developed to reconstruct such a three-dimensional (3D) image of the weld (Redmer et al. 2006; Ewert et al. 2012a). This method is very sensitive to indicate cracks and lack of fusion. The depths and shape of these defects can be reconstructed and measured. Figure 30.29 shows the image of a reconstructed crack in an austenitic girth weld in comparison to a cross-sectional metallography.

The High Contrast Sensitivity Technique was combined with planar tomography and the TomoCAR setup. It enables a significantly higher detail resolution than classical film radiography and digital laminography. The test sample BAM 5 (8 mm mild steel, Figure 30.30 left) was inspected with TomoCAR.

About 700 projections were acquired in an angle range of ±40°. Each projection was taken at 100 kV with an SNR >200. After reconstruction, it was possible to classify and size the different flaws. The weld root (Figure 30.30, right bottom image) is dominated by a lack of penetration. In the center of the weld (Figure 30.30, right central image), the welding material is presented with lower density than the base material. At the right side of the central lateral crack, the welding material did not intermix with the base material. Lack of fusion is visible. Left of the central lateral crack the welding material did intermix with the base material. In the cover layer of the weld (Figure 30.30, right upper image) a variety of lateral cracks is visible. Such a detailed image presentation cannot be achieved with X-ray film or any other NDT method.

30.6.4.7 Automated Evaluation of Digital X-ray Images: Serial Inspection in Automotive Industry

Fast digital X-ray inspection systems are used in the serial examination of industrial products, since this technique is capable of detecting flaws rather differences in their nature such as cracks, inclusions, or shrinkage. They enable a flexible adjustment of the beam direction and of the inspection perspective, as well as online viewing of the radioscopic image to cover a broad range of different flaws. This economic and reliable technique has become of essential significance for different applications. The configuration of such systems is schematically represented in Figure 30.31.
The object, irradiated from one side by X-rays, causes a radioscopic transmission image in the detector plane via central projection. The relation between the source–detector distance (SDD) and the source–object distance (SOD) determines the geometrical magnification of the image. An image converter such as an X-ray image intensifier, a fluorescence screen, or a digital detector array (DDA) converts the X-ray image to a digital image. Today, preferably DDAs are used, which have the highest efficiency for X-ray detection and allow the fastest inspection.

Light alloy castings are widely inspected in such a way, especially in automotive manufacturing. Due to imperfections of the casting process, these components are prone to material defects (e.g., shrinkage cavities, inclusions). These parts are frequently used in safety-relevant applications, such as steering gears, wheels, and, increasingly, wheel suspension components. These parts have to undergo a 100% X-ray inspection for safety.

A fully automated X-ray inspection system for unattended inspection can guarantee objective and reproducible defect detection (see example in Figure 30.32).

The decision of whether to accept or to reject a specimen is carried out according to the user’s acceptance specification. These systems are known as automated defect recognition (ADR) units.

Automated X-ray inspection is also used for a novel field of application: the check of completeness and function. This is of importance if the presence and deformation of parts have to be checked. Furthermore, distances and spatial dimensions can be examined.

The object, irradiated from one side by X-rays, causes a radioscopic transmission image in the detector plane via central projection. The relation between the source–detector distance (SDD) and the source–object distance (SOD) determines the geometrical magnification of the image. An image converter such as an X-ray image intensifier, a fluorescence screen, or a digital detector array (DDA) converts the X-ray image to a digital image. Today, preferably DDAs are used, which have the highest efficiency for X-ray detection and allow the fastest inspection.

Light alloy castings are widely inspected in such a way, especially in automotive manufacturing. Due to imperfections of the casting process, these components are prone to material defects (e.g., shrinkage cavities, inclusions). These parts are frequently used in safety-relevant applications, such as steering gears, wheels, and, increasingly, wheel suspension components. These parts have to undergo a 100% X-ray inspection for safety.

A fully automated X-ray inspection system for unattended inspection can guarantee objective and reproducible defect detection (see example in Figure 30.32).
REFERENCES


