FILM REPLACEMENT BY DIGITAL X-RAY DETECTORS - THE CORRECT PROCEDURE AND EQUIPMENT

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Abstract: New digital detectors were developed for medical applications, which have the potential to substitute the X-ray film and revolutionise the radiological technique. Digital Detector Arrays (DDA: Flat Panel Detectors, Line Detectors) and Imaging Plates (Computed Radiography) allow a fast detection of radiographic images in a shorter time and with higher dynamic than film applications. Companies report about a reduction of exposure time down to 5 – 25% in comparison to NDT film exposures. This provides together with the reduction of consumables economical (and also ecological) benefits and short amortisation periods. But this does not always provide the same image quality as NDT film. The requirements of the European and USA standards for film radiography are analysed to derive correct requirements for the digital image quality and procedures for prediction and measurement of image quality. Basically the USA standards seem to be more tolerant for these new innovative technologies. New standard proposals use signal/noise ratio and unsharpness as dominant parameters for image quality. Specialised measurement procedures are described. The properties of the new detectors can be controlled by electronics and exposure conditions. New names appear in literature like "direct radiography" and "film replacement techniques". The basic advantage of the new digital techniques is the possibility to use numeric procedures for image interpretation. Industrial radiology can be optimised for crack detection as well as for analysis of flaw depth and shape measurement. Automated flaw detection, measurement of part dimensions and detection of completeness are used for serial part inspection devices. Parallel to the development of DDA's, an extraordinary increase of Computed Tomography (CT) applications can be observed.

Introduction:

Since more than 100 years industrial radiology is based on X-ray film. Special film systems have been developed for NDT applications, which have better image quality than medical film systems but lower speed. High spatial resolution is obtained by combination of these films with lead screens instead of fluorescence screens. Medical film systems have been developed under other requirements than NDT film systems. It is always necessary in medicine to find a compromise between minimum patient dose and suitable image quality.

New digital detectors were developed for medical applications, which have the potential to substitute the X-ray film and revolutionize the radiological technique. These detectors enable new computer based applications with new intelligent computer based methods. They also can substitute film applications. These technological and algorithmic developments are highly beneficial for new NDT procedures too.

But there exist also risks. The technology was developed basically for medical applications. Its weakest point is the low spatial resolution of most of the new digital detector systems in comparison to NDT film. The application range of most DDA's is limited to lower X-ray energies (< 250 keV).

Nevertheless there exist an extraordinary economical advantage, if the classical film technique is replaced by digital detection and processing systems. Shorter processing and interpretation (P+I) cycles and the high image quality imply better product quality in a shorter time in comparison to the film technique and/or other NDT methods. This can amount to about 25% of the cycle time of P+I for mobile testing (e.g. with imaging plates) and even less than 5% for serial inspection of castings and welds. Additional savings can be taken into account due to the missing consumables in digital radiology. This is also a considerable ecological advantage.

For the detailed discussion it is necessary to distinguish between the different applications:

- Applications, which are regulated by standards (e.g. welding, casting, aircraft components)
- Non-regulated applications (e.g. pipe corrosion, wall thickness measurements)
- Automated vs manual inspection
- New areas, which never used films (e.g. computed tomography).

This paper deals basically with the regulated applications. Furthermore, it is important to analyse the testing environment, because the different digital systems are suitable for different operational conditions. It can be distinguished between:

- Mobile inspection outside.
- Mobile inspection in production areas.
- Stationary in-house inspection of different parts.
- Stationary inspection of serial parts under constant climate conditions.

There exist systems as imaging plates (IP), which are almost as weather proof as X-ray films and other systems like special flat panel detectors, which have to be protected against moisture, dust and to be handled and used in a temperature controlled area between 20° and 30° C. Life time and degradation of properties depend on handling, dose and dose power and may limit the expected benefit.

Especially for standard regulated applications, the required and obtained image quality can be measured and predicted in comparison to film radiography. Different new standard proposals for computed radiography (CR) by imaging plates and digital detector arrays (DDA) are under discussion. This shall guarantee the required image quality and avoid the application of unsuitable systems. Due to language restrictions the authors focus to the comparison of European and USA standards.

Discussion:

Comparison of Image Quality for Film and Digital Detection Systems:

X-ray film has been used since more than 100 years. The most important innovations are the development of double coated films, intensifying screens and vacuum packed flexible cassettes. The film quality has been improved over the years, but with different goals in medicine and NDT. Medical film systems are optimised for low patient dose and medium, but sufficient image quality. Special film systems yield also high image quality (e.g. mammography films). NDT films yield an excellent image quality but need 10 to 100 times higher dose for sufficient exposure. Any radiation damage of "NDT objects" is usually negligible (risks may exist for electronic products).

Therefore, NDT films are exposed to an optical density (D) between 2 and 4, which is the double of the typical value for medical applications. Critical NDT objects, as e.g. castings and weldments, require the visualisation of fine cracks and fine wall thickness changes. This leads to higher demands for the image contrast and sharpness. The basic requirements are described in several standards.

Normalized Signal/Noise Ratio and Basic Spatial Resolution:

The signal/noise ratios of industrial film systems are indirectly given in EN 584-1, E 1815, K 7627, ISO 11699-1 (see Tab. 1). Film systems are characterised by the gradient G_D (at D = 2 and D = 4 above fog and base) and the granularity σ_D at D = 2 above fog and base. The most important parameter for the perception of fine flaws is the gradient over granularity ratio G_2/σ_D, which can be used to calculate the corresponding SNR. The reader of the standards should know that the gradient over granularity ratio is the uprounded quotient of gradient and granularity limits in the standards. Tab. 1 shows the different values and system classes. Even though the different nations and committees decided to use different names and ranges for the film system classes, they nevertheless did agree on the same limit values.

The conversion of G_2/σ_D into SNR values is based on the assumption that both systems, NDT film system and digital detector array systems, provide signals (opt. Density, photo stimulated luminescence, or digital grey values), which are approximately proportional to the exposure dose. Non-linear signals have to be linearized before SNR and spatial resolution can be determined. The "W"-film systems of Tab. 1 and film fluorescence screen systems are excluded, because they have a relatively non-linear characteristic. The SNR can be calculated for linear systems by:

$$SNR = (G_2/\sigma_D) / \ln(10) \qquad (1)$$

Tab. 1: Overview about the film system classes in different standards and the corresponding SNR values and G_2/σ_D values.

System class				Minimum gradient-noise ratio at	Signal to Noise Ratio
World ISO 11699-1	Europe CEN 584-1	USA ASTM E1815-01	Japan K7627-97	D=2 above D_0	D=2 above D_0
				G_2/σ_D	SNR
T1	C1	Special		300	130
	C2		T1	270	117
T2	C3	I		180	78
	C4		T2	150	65
T3	C5	II	T3	120	52
T4	C6	III	T4	100	43
		W-A	W-A	135	
		W-B	W-B	110	
		W-C	W-C	80	

The SNR values of film are measured (see standards above) with a circular diaphragm of 100 µm diameter after exposure to a diffuse optical density of 2 above fog and base. The diaphragm area (aperture) has to be converted into a square shaped area for comparison of film to digital images or detectors. The equivalent square of a picture element (pixel) amounts to 88.6 x 88.6 µm², which corresponds to a resolution of 287 dpi. The pixel size/area is important, because the SNR depends on the detector area. The SNR increases proportional to the square root of the pixel area under same exposure conditions (same radiation quality and exposure time).
Therefore, the new standard proposals for CR and DDA radiology require minimum normalised SNR_N limits for classification (CEN: prEN 14784-1, ASTM: Z7024Z). The measured SNR_{meas} has to be corrected by:

$$SNR_N = SNR_{meas} \cdot \frac{88.6\mu m}{SR_b} \qquad (2)$$

SR_b is the basic spatial resolution (in µm), which corresponds to the effective pixel size (square root of pixel area). SR_b can be measured at different kind and manner**.** In the standard committees it was recommended to use the duplex wire method due to its simplicity (EN 462-5, E 2002). These standards provide a total unsharpness value (u_T) in µm which is equivalent to the spatial resolution. The basic spatial resolution SR_b is calculated by:

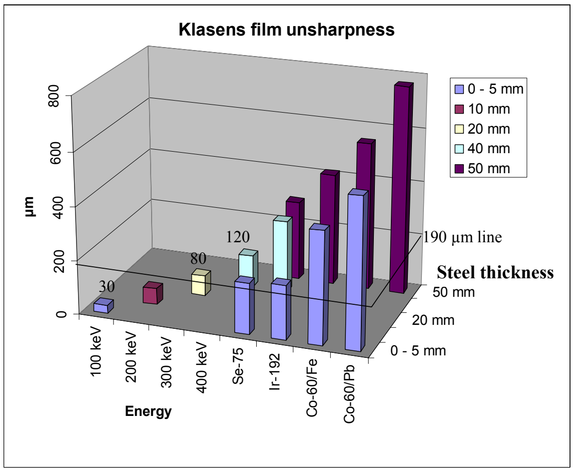
$$SR_b = u_T / 2 \qquad (3)$$

SR_b corresponds usually to the pixel size (pixel limited unsharpness) of direct converting systems (e.g. α-Se flat panel or CdTe- flat panel). It is greater than the pixel size for CR and DDA's with fluorescent converter screens.

Film Replacement on the Basis of Image Quality Parameters

The classification of a digital detector system for comparison to NDT film systems needs two parameters:

- *basic spatial resolution SR_b and*
- *normalised SNR_N as function of exposure conditions (usually speed at defined radiation quality)*.



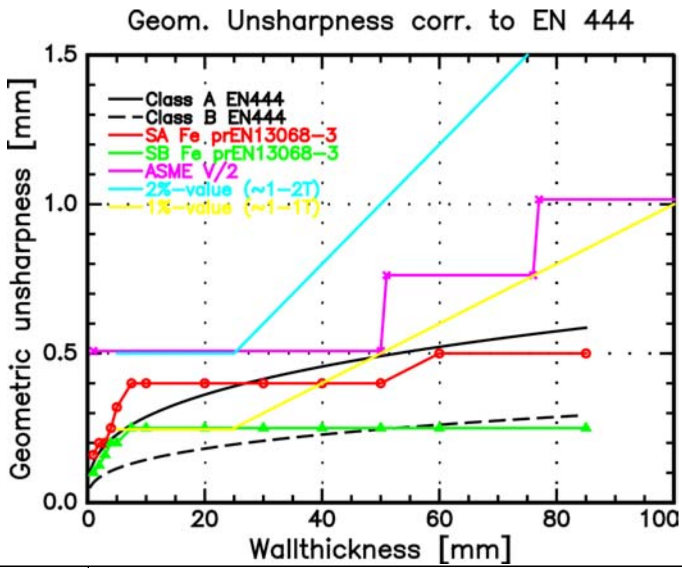


Fig. 1: Measured unsharpness of NDT film systems for different screens, materials, wall thickness and energy.

Fig 2: Geometrical unsharpness as function of wall thickness for different standards.

The concept of digital quantum efficiency (DQE), which is used in medicine for characterization of digital detectors, is more complicated and requires a complex measurement procedure. It is based on the same elements like the procedure described above. The SNR_N corresponds to the "noise equivalent quanta" at spatial frequency of zero. The ratio to the "input equivalent quanta" is considered indirectly. The standard proposals recommend calculating the speed of the used detector. It is defined as the inverse dose (in Gray), which is necessary to obtain a certain class limit of Tab. 1. Since most detectors are able to reach even the best system class, each detection system can be characterized by pairs of SNR_N classes and speed values additional to the basic spatial resolution.
For any testing problem the required image quality shall be defined. Standardized NDT applications use defined film systems, which are usually film lead screen systems. The corresponding SNR_N can than be taken from Tab. 1.
The required basic spatial resolution (SR_b) can also be determined from standards. Film systems (with lead screens) are distinguished by a very low unsharpness, which depends on radiation quality, screen thickness and screen material. Fig. 1 shows the film unsharpness values, which were measured with a microphotometer and determined by the Klasens method (E1000). These values are in general much smaller than the required geometrical unsharpness. Usually, a detector unsharpness can be accepted in the range of (or smaller than) the required geometrical unsharpness. Unfortunately, these values are not harmonized world wide. European standards define the geometric unsharpness as a function of the wall thickness for two classes (standard A and enhanced B).
ASTM and ASME standards require quite moderate unsharpness values, especially in the lower wall thickness range. The original idea was to require about the same unsharpness as the perceptible wall thickness contrast. These values are usually between 1% and 2 % of the maximum material thickness. The typical NDT testing sensitivity in USA requires the 2-2T penetrameter perceptibility, which even allows an unsharpness of 4% of the material thickness. Only the new standard E2104 (Radiographic examination of aero …) contains reduced unsharpness reqirements. Fig 2. shows a comparison of the different minimum requirements for the geometrical unsharpness of different standards. ASME V/2 is equivalent to E 1032.
As general conclusion of these standard based requirements, the user shall define the minimum required *SNR_N* (see Tab. 1) and the *basic spatial resolution* in dependence on the inspected material thickness, energy and company procedures.
The European EN 444, EN 1435 and EN 12681-5 require for instance:
1st a minimum geometric unsharpness as function of wall thickness (w) and testing class and
2nd film systems between C3 and C5 ($SNR_N \geq 120$ … 180 at D=2) as function of wall thickness, radiation energy and testing class.

Table 2: Required spatial system resolution in dependence on energy and wall thickness					
Radiation source	Wall thickness w [mm]	Class IPA		Class IPB	
		Max. Pixel[1] Size [µm]	Double wire IQI-number[2]	Max. Pixel[1] size [µm]	Double wire IQI-number[2]
X-ray Up ≤ 50 kV	w < 4	40	> 13[3]	30	>> 13[4]
	4 ≤ w	60	13	40	> 13[3]
X-ray 50 < Up ≤150 kV	w < 4	60	13	30	>> 13[4]
	4 ≤ w < 12	70	12	40	> 13[3]
	w ≥ 12	85	11	60	13
X-ray 150 < Up ≤ 250 kV	w < 4	60	13	30	>> 13[4]
	4 ≤ w < 12	70	12	40	> 13[3]
	w ≥ 12	85	11	60	13
X-ray 250 < Up ≤ 350 kV	12 ≤ w < 50	110	10	70	12
	w ≥ 50	125	9	110	10
X-ray 350 < Up < 450 kV	w < 50	125	9	85	11
	w ≥ 50	160	8	110	10
Yb 169,Tm 170		85	11	60	13
Se 75, Ir 192	w < 40	160	8	110	10
	w ≥ 40	200	7	125	9
Co 60		250	6	200	7
X-ray Up > 1MeV		250	6	200	7
NOTE:	[1]If magnification technique is used, double wire IQI-readout is required only. [2]The given IQI-numbers indicate the readout value of the first unresolved wire pair corr. to EN 462-5. [3]The symbol ">13" requires the 13th wire pair to be resolved. [4] The ">>13" requires the 13th wire pair to be resolved with > 50% dip between the maxima. Up - Tube voltage.				

The total unsharpness u_T is substituted now by the maximum geometrical unsharpness u_g which is calculated in EN 444 by:

$$u_g = \frac{1}{a} \cdot w^{1/3} \qquad (4)$$

with a = 15 for class B testing and a = 7.5 for class A testing and
with w - in mm.
The "European" equation 4 enables the calculation of the required pixel size of the detector for a European testing problem. Due to the difference between u_g and SR_b the recommended pixel size is one half of u_g. If the detector unsharpness is higher than the required one, a magnification technique should be used. Tab. 2 summarizes the discussion. It gives some recommended values for application of CR systems (prEN14784-2).
It is pointed out that the described procedure above focuses to the strict applications of the E 444 based standards. There exist a variety of testing tasks, which do not need the low unsharpness requirements of testing class B or even class A. Companies can define its own limits. This is the typical case for automated X-ray inspection systems. The

minimum unsharpness is derived from fracture mechanics and time constrains. The European standard EN 13068-3 (Radioscopy) allows higher unsharpness values in the lower material thickness range, but requires the usage of lower radiation energy to compensate with increased contrast.

The ASTM/ASME standards are characterized by moderate requirements for the unsharpness, especially in the low wall thickness range. This promotes the application of new digital techniques considerably. The tester should know about the risk of reduced probability of detection for fine details. Usually the written procedure of the company defines the required sharpness in dependence on the testing problem.

Some digital detectors are characterized by considerable differences in its spectral sensitivity. Fluorescence screen based DDAs and CR have a higher sensitivity for radiation of low energy than film lead screen systems. This contributes to an increased sensitivity against scattered radiation. The effective object contrast decreases in comparison to film systems. This effect must be considered and the scattered radiation should be reduced by application of lead or steel screens for filtration. A typical value for CR systems (steel inspection) is the application of 3 times thicker lead screens than typical for film based inspection. The human eyes will percept the Contrast/Noise Ratio (CNR) instead of the SNR. Due to the difficulties of the measurement, the SNR limits were chosen for the standard procedures. Nevertheless, the contrast IQIs (e.g. wires or step hole penetrameters) must be used for applications to guarantee that the sufficient CNR is obtained.

Available Digital Detector Systems:

Computed Radiography:

Imaging plate systems are available for NDT since more than 10 years. They can be used as filmless radiography technique, which is also known as computed radiography (CR). Imaging plates are exposed as film and scanned by a laser scanner to obtain a digital radiograph. Tab. 3 summarises the advantages and disadvantages.

Table 3:

The advantages of the IP-Technology are:	Disadvantages are:
High linearity.	Some systems have limited spatial resolution.
High dynamic range > 10^5 .	High sensitivity in the low energy range.
High sensitivity.	Sensitive to scattered radiation.
1000 exposure cycles reusable.	
No darkroom process.	
Image processing is possible.	

Imaging plates (IP) are read by a LASER scanner producing a digital image without any developing process [1]. After erasing the remaining latent image with a bright light source, the same IP can be recycled up to more than 1000 times. An IP consists of a flexible polymer support which is coated with the sensitive layer. On top it is covered with a thin transparent protective layer. The sensitive layer of the most common systems consists of a mixture of BaFBr doped with Eu^{2+}. X-ray or gamma ray quanta result in an avalanche of charge carriers i.e. electrons and holes in the crystal lattice. These charge carriers may be trapped at impurity sites. Red laser light (600-700nm) excites electrons trapped in a Br^- vacancy (FBr^- centre) to a higher state. Upon return to its ground state blue photons (390nm) are emitted. This process is described as photo stimulated luminescence (PSL).

The available systems of phosphor imaging plates and corresponding laser scanners cover radiation dose differences up to 10^5 in a non-linear scale (log or square root) or 10^3-10^4 in a linear scale. This feature reduces the number of exposures for objects with high wall thickness difference. It also compensates for wrong calculated exposure times. The number of so called "test exposures" is reduced. The system provides more grey levels than the human eye can distinguish. Image processing has to be applied. CR systems are also suitable for mobile inspection under difficult weather conditions. Only the scanner needs weather protection.

There exist different systems for CR with different properties (SNR and spatial resolution). Similar to film radiography, the appropriate system has to be chosen according to a specific application. Fig. 3 presents a comparison of computed radiographs of a duplex wire IQI as model for fine structures like for instance fine cracks.

Different IP's were tested. All of them were exposed at 220 kV and read out with an AGFA scanner with 900 dpi (System AGFA DPS, 28 µm pixel size; laser spot about 40 µm). The FUJIFILM IP (ST-VN) was optimised for a scanner with 100 µm pixel size (AC3). The Agfa NDT (MD10 modified) was developed for a 50 µm scanner and the prototype "AGFA blue" for high resolution applications. The last one resolves all line pairs and has a unsharpness better than 100 µm (MTF measurements: 80 µm). It is the slowest detector. It is about 100 times slower than the fast FUJIFILM IP related to the same SNR but only 10 times slower related to the normalised SNR_N.

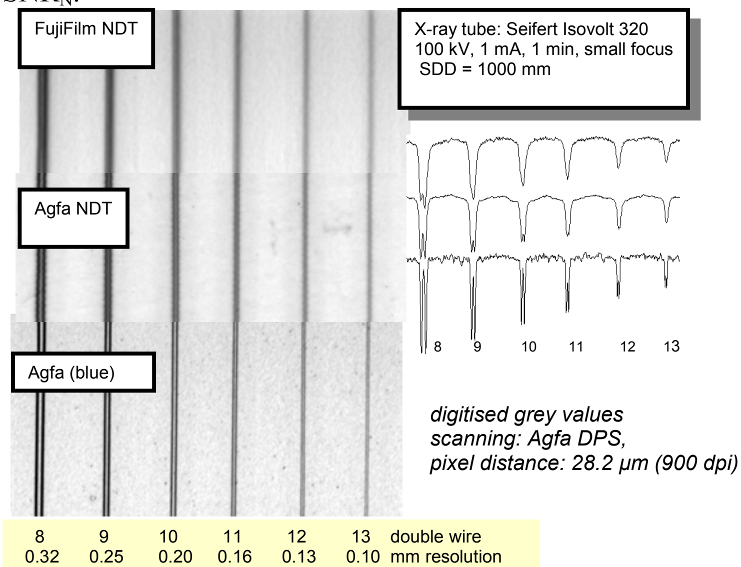


Fig. 3: Computed radiographs and profiles taken with different types of imaging plates and a high resolution scanner (DPS of AGFA) of a duplex IQI corresponding to ASTM E2002 and EN 462-5. The spatial resolution values, read of the IQI-radiographs, varies from FujiFilm NDT with 250 µm over Agfa NDT with 160 µm to Agfa blue with better than 100 µm.

Digital Detector Arrays:

Flat panel detectors, also called **Digital Detector Arrays** (DDA), may become an alternative technology for both, computed radiography and image intensifier based real time radiography. They are mostly based on amorphous silicon detector arrays with thin film transistors for read out control and photo diodes as light detectors, which are covered with a fluorescence screen for light conversation [2]. Recently developed detector systems use a direct converting process. Amorphous selenium or CdTe-systems permit the separation of charges, generated by high energy radiation, and read this charges by micoelectrode systems [2]. Direct converting systems are characterised by a higher inherent spatial resolution than the systems which use fluorescence screens. Flat panel systems entered the NDT market in a relatively short time. They substitute film radiography and radioscopy systems and open new possibilities for the application of computed tomography (CT).

DDAs allow a fast and cost efficient inspection. Mostly they are used in X-Ray cabinets. They are usually not weather proof and need air conditioned environment. In case of serial part inspection, automated defect recognition systems are used, or a human inspector examines the radiographic images and performs the accept/reject decision. For visual inspection the high dynamic range ~64000 gray levels has to be adapted to the ~60 gray levels, which can be distinguished by the inspector at a usual monitor. Special image processing algorithms can be applied to enhance the perception of potential defects.

For automated inspection the high dynamic range of most DDAs reduces the effort for adjustment and it also reduces the amount of positions for inspection. The fast data acquisition and the ability to allow testing with a high dose (mA) permits very short inspection cycles. DDA systems can be classified with the above mentioned principles and be qualified for film replacement. Nevertheless it is necessary to use special test parts with natural or artificial defects to ensure a safe and reliable inspection on a daily base. This applies especially for automated systems.

Most of the DDA systems degrade during its life time. Some artefacts appear and create pseudo structures which may influence the perception of defects. A test procedure has to be defined to prove a stable inspection over the life time of the DDAs. Most DDAs are distorted by so called “bad pixels”, which disturb the application of this

technology. Pixels with low signal intensity and clusters of pixel defects create problems for visual inspection. For automated systems the most critical disturbance appears from non-linear pixels, noise pixels and clusters. Also image lag may produce pseudo structures. Image lag is one of the most serious problems in CT systems because the radiographic measurement of the material thickness as function of the penetration angle depends on real separate images without signal transfer from the image, taken before.
Parallel to the development of 2-dimensional detectors, improved **line cameras** open new ways for mobile applications in radiology. High resolution detector lines and time delayed integrating (TDI) lines speed up the data acquisition and lead to an image quality that is sufficient for weld inspection and casting production surveillance. Mobile CT-applications allow additionally the determination of the flaw depths and shape, which was not accessible by radiography before [3].

Conclusions:

The new digital detectors (imaging plates, flat panel detectors and line detectors) are suitable for film replacement. Since the requirements to film radiography for medical and NDT applications are different, standardized algorithms are necessary to measure the image quality. The properties of NDT films are described in different standards. The basic parameters are the normalized SNR_N and the basic spatial resolution SR_b. SNR_N limits for classification can be derived form EN 584-1, E 1815, JIS 7627 and ISO 11699-1 and are given in Tab. 1. Digital detectors should have the same or better SNR_N than the film systems to compare. The minimum required SR_b can be derived from the geometrical unsharpness (u_g) requirements of standards as EN 444, EN 1435, ISO 5579, E 1032 and E1742. The recommended SR_b value is about ½ of the u_g requirement, which depends mostly from the material thickness. Tab. 2 gives an example for a European proposal for NDT with imaging plates. Due to different spectral properties of the digital detectors and the higher unsharpness than NDT film systems, the CNR may be smaller than in film radiography. Optimized filters have to be used and IQIs must be applied to guaranty the expected perception of flaws.
Imaging plates are an excellent tool for digital radiography. They are suitable for stationary and mobile inspection, also under difficult weather conditions. There exist no limitations of the radiation energy and dose. DDAs are suitable for in-house inspections, because they need stabilised temperature and moisture conditions. They are an excellent tool for serial part inspection and CT. Due to its high image quality, dynamic and speed they dominate stationary applications and speed up film replacement. Bad pixels and image lag limit its application presently.

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