

# Minimum Requirements for Digital Radiography Equipment and Measurement Procedures by Different Industries and Standard Organizations

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## Abstract

The digital photography has almost completely substituted the film photography. The film replacement is also fast progressing in medical X-ray radiography. This process is slower in NDT and especially in Europe. Reasons for the hesitating change to digital radiography (RT-D) in NDT are the necessary time for adoption of standards and the conservative request for film RT by auditors and NDT managers for applications in large plants and at construction areas. The fast serial inspection for small castings is already almost completely dominated by RT-D due to the cost effective short exposure and interpretation times. Standards were developed in parallel at CEN, ISO, ASTM and ASME. Unfortunately, the standard practices are different and the requirements on image quality and useable hardware are different too. The first standard series on Computed Radiography were developed and published by CEN and ASTM in 2005. Harmonized classification and qualification standards are available but the published practices are different. ASTM has developed the first standards for application of Digital Detector Arrays (DDA) in 2010. The first digital RT ISO standard practice is ISO 17636-2 (2013), which describes the practice for application of DDAs and Imaging Plates for weld inspection. At the first time this standard provides requirements for the selection of suitable hardware. Minimum image quality requirements are specified in analogy to film radiography and 3 Compensation Principles are defined to enable the application of a wider range of digital detectors. A comparison of the different international digital RT standards is given and first experiences with ISO 17636-2 are discussed. New standards on RT wall thickness and corrosion measurements (EN 16407, film and digital) have been developed recently.

**Keywords:** NDT, X-Ray, digital detectors, standards, radiographic procedures, unsharpness, basic spatial resolution. Contrast sensitivity

## 1. Introduction

The visibility of flaws and image quality indicators (IQI) by human operators have been *discussed* for film radiography (RT-F) over decades. If operators follow the current standard ISO 17636-1 or ISO 5579 on film radiography, use the recommended NDT film systems and exposure conditions, the achievable contrast sensitivity is in the order of 0.5 - 10% thickness resolution, depending on the IQI used and of the penetrated material thickness. In the last 15 years film replacement has been discussed in analogy to the success story of digital photography. Operators had to be trained to understand the differences between film and digital industrial radiography and the essential parameters for optimization of the image quality. Two different user groups have to be brought together: film radiographers who want to change from film to digital techniques and radioscopy users which never used any film RT before.

The image quality in digital industrial radiology (DIR) depends mainly on the exposure conditions and the properties of the digital detectors. Operators need rules and reliable parameters for detector selection and correct hardware and exposure conditions. This is the basic purpose of standardization. Different new standards were developed and published during the last 10 years. Trends, requirements and practices of four international standardization organizations will be compared in this paper. These are ISO, CEN, ASTM-International and ASME BPVC Section V, Article II. ASME took over some requirements of ASTM-International, but does also describe some different rules.

Many parameters influence the result of digital radiographs, but only three are essential for the achievable contrast sensitivity. These essential parameters are the basic spatial resolution of the image ( $SR_b^{\text{image}}$ ), the Signal-to-Noise Ratio (SNR) and the specific contrast ( $\mu_{\text{eff}}$ ). The equivalent penetrameter sensitivity (EPS), which corresponds to the material thickness

sensitivity of plate hole IQIs as defined by ASTM E 746, E 1025 and E 1742, can be calculated, if the essential parameters are quantitatively known. A similar approach can also be applied to predict the visibility of wire IQIs.

The basic spatial resolution of a detector ( $SR_b^{\text{detector}}$ ) is considered as a quantitative value for its effective pixel size. It is the major parameter, which allows the user to decide if a digital system can be applied for a certain inspection task. Different standards provide different limits of the permitted basic spatial resolution, geometric unsharpness or image unsharpness values. Typical examples are the standards ISO 17636-2, ASTM E2698 and the MAI guidelines for the use of Digital Detector Arrays and Computed Radiology [1, 2].

The related studies were performed with Computed Radiography (CR) and Digital Detector Arrays (DDA) in comparison to digitized film radiographs. Computed radiographs, taken with imaging plates, achieve similar IQI visibility than film radiographs. In many cases they achieve only the performance of testing class “A” (basic) as defined in the standard ISO 17636-2 and fulfil completely the requirements of ASME BPVC section V article 2. Radiography with DDAs can achieve typically much better IQI visibility than film radiography and CR, even at short exposure times. Considering the optimum exposure conditions and selecting the suitable detectors, digital radiography can be applied to a broad range of X-ray applications, including inspection of pipeline welds, castings, electronic assemblies, wheels, rails, aerospace, bridges and many other industrial uses for technical, environmental, safety and economic advantages.

## **2. Standards for Digital Radiography**

### ***2.1 Overview on available standards***

After completion of international radiosopic standards about 20 years ago, new rules and standards were required for film replacement. The quality of film radiography was the basis for contractual agreements between NDT service providers and manufacturers of products and industrial facilities as well as maintenance providers over more than 40 years. All new digital RT standards for film replacement should provide an image quality equal or better than film RT to enable a comparable flaw detection rate as compared to film RT. The first set of international standards on computed radiography (CR) was published at CEN and ASTM-International in 2005. This initiated a controversial discussion when operators started to perform RT with imaging plates. DDA standards were published at ASTM-International in 2010 based on different requirements and users started to work with these standards. See Table 1 for a comparison of major RT industrial standards. Furthermore, the document “Guidelines for the Use of Digital Detector Arrays and Computed Radiology for Aerospace Casting Inspections” (USA) [2] was published as a guideline for digital radiography practice and its training. This guideline deviates from other standards. New ASTM standard revisions will consider some aspects of the MAI document. In parallel the International Atomic Energy agency published the guideline on Training, Examination and Certification in Digital Industrial Radiology Testing (RT-D) [3]. Contents and training hours differ since the documents were developed in parallel. ISO revises the syllabus ISO TR 25107 for personnel training to be conform to ISO 9712. Training requirements for digital Radiography will be implemented on the basis of the IAEA guideline.

**Table 1:** Relevant standards of ISO, CEN, ASTM and ASME BPVC Section V, for RT-F and RT-D training (2013)

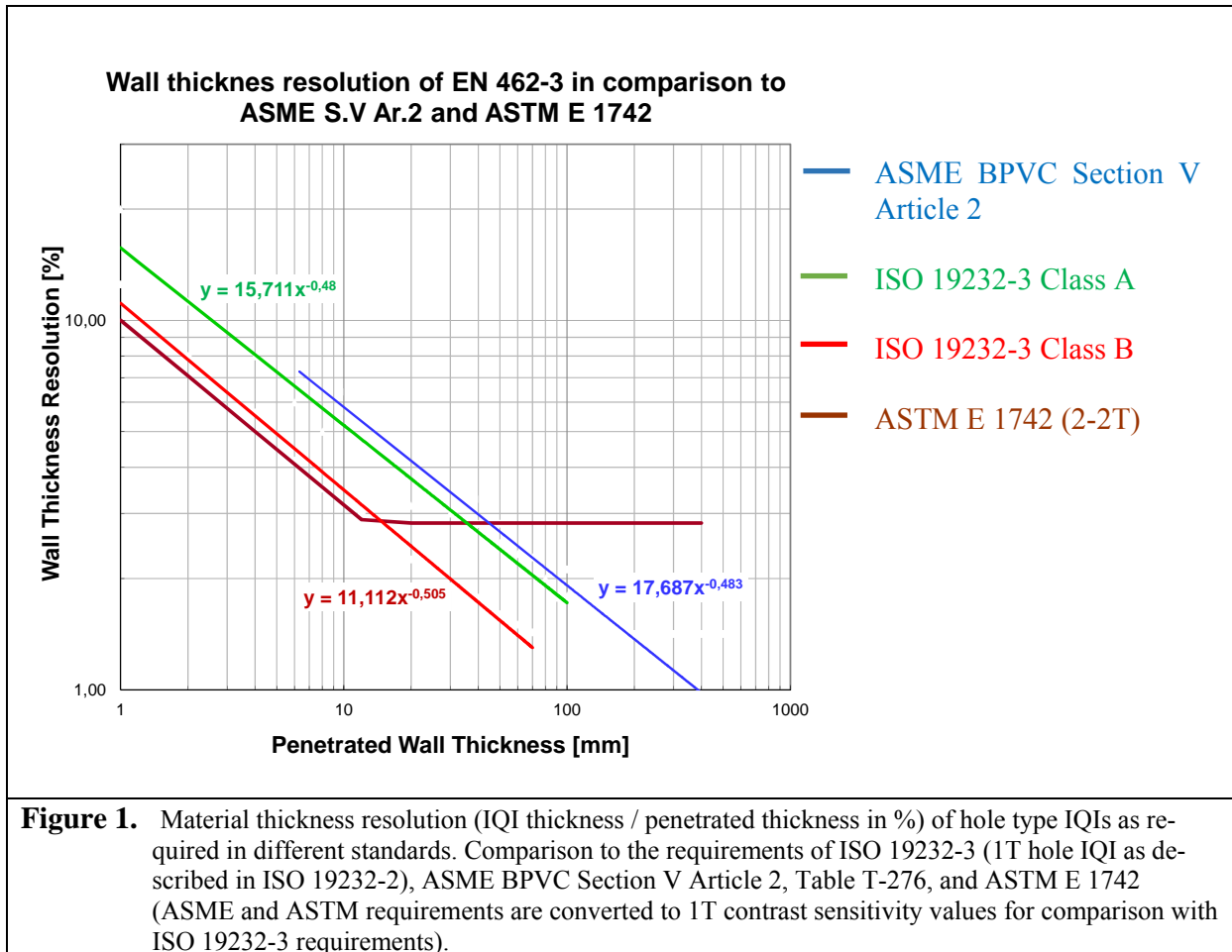
Method	Standard Organization	Qualification	Stability tests	Guide	General practice	Welding General	Welding Practice	Welding evaluation	Casting Practice	Casting Catalogue	IQI Contrast	IQI Spatial resolution
RT-Film	ISO	11699-1	11699-2		5579	17635	17636-1	10675			19232-1 19232-2	19232-5
	CEN EN	584-1	584-2		444	17635	17636-1	10675	12681		462-1, 462-2	462-5
	ASTM E	1815		94	1742		1032		1030	155, 186, 192 242, 272, 280 310, 390, 446 505, 689, 802 1320, 1648	747, 1025	2002
	ASME BPVC				Section V Article 2		Section V Article 2 Appendix A	Section V Article 1	Section V Article 2 Appendix 7		Section V Article 2 Appendix C, D	
RT-S: Radioscopy Fluoroscope Intensifier DDA- real time	ISO					17635		10675			19232-1 19232-2	19232-5
	CEN EN	13068-1	13068-2	13068-1	13068-3	17635		10675			462-1, 462-2	462-5 2002
	ASTM E	1411		1000	1255		1416		1734	2422 2660, 2669	747, 1025, 1647	
	ASME BPVC				Section V Article 2 Appendix 1,2,3				Section V Article 2 Appendix 7		Section V Article 2 Appendix C, D	
Film Digitisation	ISO	14096-1	14096-1		14096-2							
	CEN EN	14096-1	14096-1		14096-2							
	ASTM E	1936								2422, 2660, 2669		

Method	Standard Organization	Qualification	Stability tests	Guide	General practice	Welding General	Welding Practice	Welding evaluation	Casting Practice	Casting Catalogue	IQI Contrast	IQI Spatial resolution
RT-D: CR	ISO	16371-1	16371-1			17635	17636-2 10893-7	10675			19232-1,2	19232-5
	CEN EN ASTM E	14784-1 2446	14784-1 2445	2007	14784-2 2033	17635	17636-2	10675		2422 2660, 2669	462-1, 462-2 747 1025	462-5 2002
	ASME BPVC				Section V Article 2 Appendix 8		Section V Article 2 Appendix A	Section V Article 1	Section V Article 2 Appendix 7		Section V Article 2 Appendix C, D	
RT-D: DDA	ISO					17635	17636-2	10675			19232-1 19232-2	19232-5
	CEN EN ASTM E			2736	2698	17635	17636-2	10675		2422, 2660, 2669	462-1, 462-2 747 1025	462-5 2002
	ASME BPVC				Section V Article 2 Appendix 9		Section V Article 2 Appendix A	Section V Article 1			Section V Article 2 Appendix C, D	
Radiation Source size	ISO				3999-1							
	CEN EN ASTM E				12679 1114							
Focal spot Size	ISO											
	CEN EN				12543-1/5							
Computed tomography	ASTM E				1165, 2903							
	ISO			15708-1	15708-2							
	CEN EN	16016-4		16016-2/1	16016-3							
DICONDE Data format	ASTM E	1695		1441, 1672	1570, 1935				1814			
	CEN EN				CR 13935							
	ASTM E				2663, 2699, 2669, 2738, 2767							

### 3. Image Quality Parameters in Digital Radiography

#### 3.1 Measurement of Sensitivity with Image Quality Indicators (IQI)

The sensitivity of radiographs is typically evaluated by image quality indicators (IQI). European users apply mostly wire IQIs, or in some areas step hole IQIs (see ISO 19232) with 1T holes (1T-hole: diameter corresponds to IQI step thickness). US standards as ASME (BPVC Section V, Article 2) require typically plate hole IQIs, but permit also wire IQIs. The plate hole IQI design is described in ASTM E 1025 and E 1742. In both cases the standards require a material thickness contrast sensitivity (CS) which improves about with 1/square root of the material thickness (see Fig. 1).



The required thickness sensitivity is similar in the ASME BPVC Section V, Article 2, Table T-276, and ISO 19232-3, testing class A. Some ASTM standards as e.g. ASTM E 1742 and ASTM E 2104 require a thickness sensitivity of 2% of the material thickness (2-2T, equivalent to 2.8-1T). Since the IQIs could not be manufactured in the past with very small holes, the required hole diameter  $d$  does not change below  $d = 0.5 \text{ mm}$  for a 2T hole. The consequence is that the plate hole IQIs (2-2T sensitivity) show for inspections below 12 mm (1/2") a sensitivity which corresponds to the one of ISO 19232-3, testing class B. At higher material thickness the ASTM sensitivity (2-2T) stays behind the requirements of the other standards (see Fig. 1). This makes it difficult to compare the sensitivity of radiographs and the corresponding probabilities of detection internationally.

ASTM E 1025 (plate hole IQIs) and ASTM E 747 (wires) define the thickness contrast sensitivity quantitatively as EPS (equivalent penetrameter sensitivity). The EPS value is defined for hole type IQIs in ASTM E 1025 by

$$EPS(\%) = \frac{100}{t_{material}} \sqrt{\frac{T_{IQI} \cdot d_{hole}}{2}} \quad (1)$$

with

EPS	- Equivalent penetrameter sensitivity in % of material thickness
$t_{material}$	- Thickness of penetrated material
$T_{IQI}$	- Thickness of IQI
$d_{hole}$	- Diameter of IQI hole

The EPS value is a reference for the 2T hole visibility. The consequence is that the European percentages, which are related to 1T holes have to be converted by square root of 2 (= 1.414). Two percent EPS means 2.8 % wall thickness contrast, if the 1T hole shall be visible instead of the 2T hole (see also Fig. 1).

The quantitative measurement of the EPS is based on the visibility evaluation of the hole type IQIs at the radiographic image by a human operator, depending on the IQI thickness and hole diameter. The visual evaluation depends on the (subjective) individual operator and the results scatter. In digital radiology the viewing of images is performed on a monitor, instead on a light viewing box. This may change the result of visual evaluation of the image quality. In order to quantify the EPS by objective measurements the influencing parameters were investigated in [4, 5].

### 3.2 *The essential parameters for digital radiology*

The following essential parameters are controlling the contrast sensitivity and therefore the visibility of IQIs in a digital grey level image:

- **Basic spatial resolution** ( $SR_b$ ),
- **Signal-to-noise ratio** (SNR),
- **Relative specific contrast** ( $\mu_{eff}$ ), which is the effective attenuation coefficient (including scatter effects).

The definition and detailed explanations are given in [4, 5].

## 4. Qualification of digital detectors

### 4.1. General Remarks

International standards require a minimum contrast sensitivity (e.g. EPS - equivalent penetrameter sensitivity, see ASTM E 1025 and E 746) as shown in Fig. 1 and a maximum unsharpness limit depending of the penetrated material thickness. The standards provide for wire and hole type IQIs minimum sensitivity values. These values indicate a combined effect of contrast to noise ratio (CNR) and unsharpness or basic spatial resolution of the image ( $SR_b^{image}$ ), respectively. Duplex wire or line pattern IQIs provide the unsharpness and basic spatial resolution values.

In film radiography the film unsharpness depends more on the lead screen thickness and on the used radiation energy (keV) than on the AgBr grain size. The unsharpness value amounts to about 10 – 30  $\mu m$  between 100 and 300 keV. Typically, the geometric unsharpness resulting from the focal spot size and distance to the object is larger than these values of the NDT film systems and determines the total unsharpness  $U_T = 2 \cdot SR_b^{image}$ .

The inherent unsharpness of digital detectors is typically higher than the one of NDT film systems. Computed radiography systems, which are currently used in NDT were classified with a  $SR_b^{detector}$  of 40 – 160  $\mu m$  [10]. Digital detector arrays (DDA) are currently available for NDT applications with  $SR_b^{detector}$  of 80 – 400  $\mu m$ .

ISO 17636-2 requires for digital radiography the application of digital detectors with  $SR_b^{detector}$  of 40 – 400  $\mu m$  depending on the material thickness if no magnification is used. Detec-

tors with higher  $SR_b^{\text{detector}}$  may be applied on the basis of the compensation principle II of ISO 17636-2.

**Consequently the basic spatial resolution of digital detectors is the most important qualification parameter, because this value is essential for the standardized application.**

#### 4.2 Computed Radiography

Imaging Plates (IP) are routinely used in medicine and biomedical autoradiography since more than 20 years. Several systems are also offered for NDT applications [10, 11]. 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. Any remaining latent image can be erased with a light source (e.g. halogen, incandescent). So, the same IP can be re-used up to more than 1000 times if carefully handled. Less expensive CR scanners require manual handling of the imaging plates. This may reduce the IP cycle to less than 100 cycles before scratches disturb the digital images.

CR systems are substituting film applications, especially for mobile NDT. Typical applications are the quality assurance of welds and measurement of wall thicknesses and monitoring of corrosion and erosion in pipes [12, 13]. Nowadays, CR is also applied to optimize manual maintenance of valves, fittings and other armatures. Radiographic imaging permits the evaluation of the functionality.

Imaging plates are basically sensitive for radiation of lower energy ( $< 250$  keV). They can also be applied for high energy radiography in the MeV range, if scattered radiation is properly shielded and lead and steel filters are applied in front of the plate. BAM applies high energy radiography and tomography in its HEXY Lab (High Energy X-ray laboratory) in the range of 1-12 MeV.

The properties of the digital images are controlled by the properties of the IP and the scanner. The properties of the IPs determine the speed and spatial resolution (Unsharpness) of the digital images if a suitable scanner is used. Typically 3 types of IPs are in use for NDT (see Tab. 2):

**Table 2.** General subdivision of imaging plate types in relation to the old film type classification in coarse, fine and very fine grained.

IP-plate type	Speed	Unsharpness, Granularity	Sensitive layer thickness	Colour	Application
Medical, NDT gamma, NDT high energy	fast	high	thick	white	Corrosion, Wall thickness
NDT standard	medium	medium	medium	white	Welding, Casting
NDT high resolution	slow	low	thin	blue	Welding

The subdivision of IP types of Tab. 2 is used in labs traditionally in analogy to traditional film description. The classification of CR systems by EN 14784-1, ISO 16371-1 and ASTM E 2446 is based on the achieved  $SNR_N$  ( $SNR$  normalized by basic spatial resolution) and exposure time (ISO speed) and the measured basic spatial resolution of a CR system. In the meantime, all available NDT CR systems exceed the required  $SNR$  values ( $SNR_N > 130$ ) for best IP class (Tab. 3a). New limits are in discussion for a new classification standard at ASTM and CEN. CR systems shall be classified in future by the maximum achievable  $SNR_N$ , interpolated  $iSR_b^{\text{detector}}$  and best achievable EPS, which depends on the manufacture process and the inherent fixed pattern structure. The classification will be based on performance levels

to distinguish from the old system classes. The required SNR<sub>N</sub> limits were increased to be conform to ISO 17636-2 class A and B. CR level I – III will substitute system class IP 4 – 6. Instead of the measured SR<sub>b</sub><sup>detector</sup> value Y the new scheme will provide limits for iSR<sub>b</sub><sup>detector</sup> and the achievable EPS value as given in Table 3b.

<b>Table 3a.</b> Classification scheme of EN 14784-1 and ISO 16371-1 by system classes. The CR systems are classified by the maximum achievable SNR <sub>N</sub> (IP 1 – 6) and the basic spatial detector resolution SR <sub>b</sub> <sup>detector</sup> (Y).		<b>Table 3b.</b> New classification scheme by performance levels as given in the draft revision of ASTM E 2446 (2014). Additionally, a specified EPS performance is required.			
<b>System class CEN</b>	<b>Minimum normalised SNR</b>	<b>CR System Classification</b>	<b>Minimum SNR<sub>N</sub> (normalized to SR<sub>b</sub>=88.6 μm)</b>	<b>Maximum iSR<sub>b</sub><sup>detector</sup> value [μm]</b>	<b>Maximum achieved by E 746</b>
IP 1/Y	130	CR Special	200	50	1.00
IP 2/Y	117	CR Level I	100	100	1.41
IP 3/Y	78	CR Level II	70	160	1.66
IP 4/Y	65	CR Level III	50	200	1.92
IP 5/Y	52				
IP 6/Y	43				
Note 1: The normalized SNR values of Table 1 are similar to those of EN 584-1. They are calculated by SNR= log(e) (Gradient/Granularity) of Table 1 in EN 584-1. The measured SNR values are calculated from linearised signal data.					

Since the classification result alone does not allow the sufficient comparison of CR-systems for users, further qualification parameters will be required in certification documents. The committee ASTM E 07 decided to classify and qualify CR systems and publish the data in similar graphs as required in ASTM E 2597 for DDAs. Fig. 2 shows an example for the proposed spider net graph presentation. This graph permits the comparison of qualified CR systems with film systems based on ISO 11699-1 and ASTM E 1815 and DDAs based on ASTM E 2597.

The parameters of the graph are based on the following measurements at scanner parameter sets given by the manufacturer:

**iSR<sub>b</sub><sup>detector</sup>:**

See ISO 17636-2, Annex C

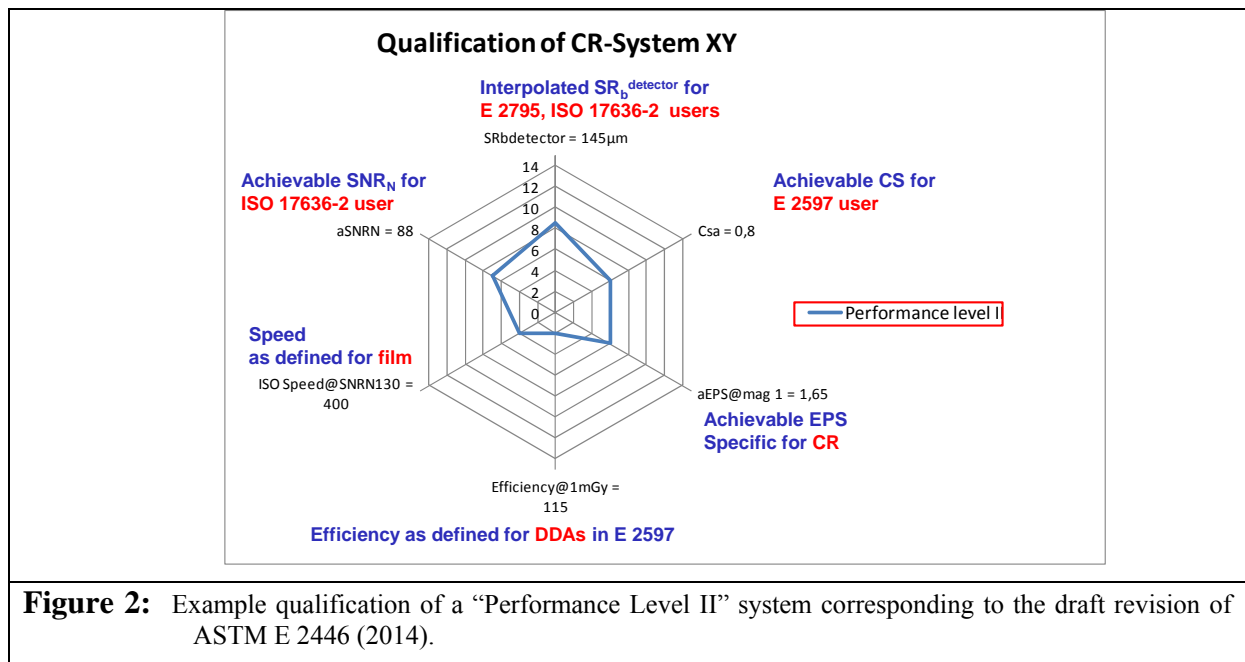
**Achievable CS:**

CS is determined by 100/CNR determined from a 5% thickness step measurement and given in % of material thickness related to a 19 mm (3/4 inch) absorber. This value should be as small as possible for good systems. It typically improves with increasing pixel size of the scanner. The value is determined after an exposure to 90% of the maximum grey value achieved with the scanner parameter set which is recommended by the manufacturer.

**Achievable EPS:**

The detector is exposed behind an absorber plate of 19 mm (3/4 inch) of mild smooth steel and the IQIs of ASTM E 746 at 220 kV. The just visible hole row is determined by the 50% method and given in % EPS. The value is determined after an exposure to 90% of the maximum grey value achieved with the scanner parameter set which is recommended by the manufacturer.





### Efficiency:

The efficiency is determined for 220 kV and an 8 mm Cu filter in front of the tube port corresponding to ASTM E 2597. It corresponds to the  $SNR_N$  at 1 mGy exposure of the detector. This value enables the users of CR the comparison with the sensitivity of DDAs.

### ISO speed:

It corresponds to the inverse exposure dose in Gy at the  $SNR_N$  of the achieved classification according to table 3b.

### Achievable $SNR_N$ :

The achievable  $SNR_N$  is determined for an exposure corresponding to ASTM E 2446 and EN 14784-1 or ISO 16371-1 at 220 kV and an 8 mm Cu filter in front of the tube port with the step exposure method or the step wedge method. The value is determined after an exposure to 90% of the maximum grey value achieved with the scanner parameter set which is recommended by the manufacturer. It permits the evaluation of the CR system according to the requirements of ISO 17636-2.

Additionally quality and functionality tests will be standardized. These tests will assure a minimum quality and provide additional qualification data. Table 4 gives an overview about these tests.

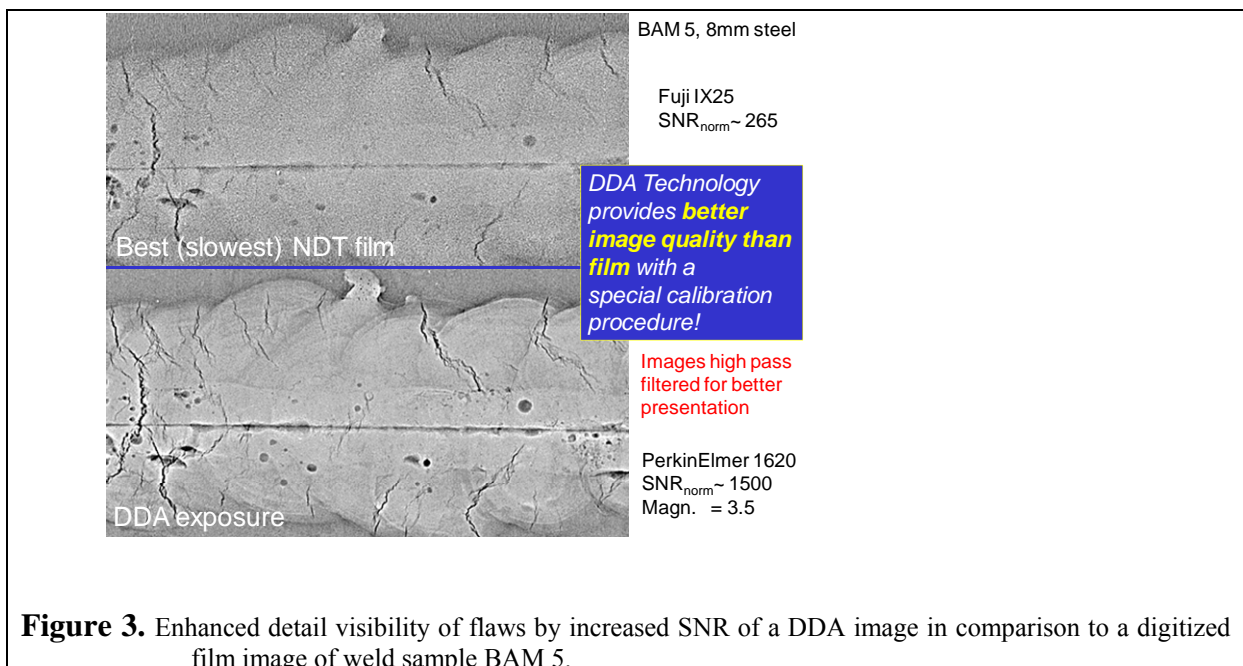
### 4.2 Digital Detector Arrays

The image quality depends on the basic spatial resolution ( $SR_{b,image}$ ), the effective attenuation coefficient ( $\mu_{eff}$ ) and the signal to noise ratio (SNR) in digital radiology [4, 5]. DDAs are always calibrated before usage to equalize the different characteristics of the detector elements. This avoids image distortions by fixed pattern noise due to differences in the detector elements and the electronics. Consequently, the image noise depends dominantly on the photon statistics. This can be exploited for radiography with high SNR and improved contrast sensitivity. DDA systems achieve a significantly higher SNR and better contrast sensitivity than imaging plates and films, if they are properly calibrated.

**Table 4.** Tests for qualification of functionality as described in E 2446 and E 2445 (Draft 2014)

Required Test	Required Result
Geometric Distortion (by spatial linearity image quality indicators in Type I Test Phantom)	Fail if distortion > 2%
Laser Jitter (by T-target in Type I CR Test Phantom)	Not permitted, Straight and continuous edges required
Laser Beam Scan Line Integrity (no test object required)	Not permitted
Scan column dropout (no test object required)	Not permitted
Scanner Slippage (by homogeneous strip slippage target in Type I CR Test Phantom)	Not permitted
Imaging plate Artifacts (no test object required)	Not permitted
Erasure (high absorption object required)	Fail if > 2%
Shading or banding (by homogeneous plate, three shading image quality targets in Type I)	Fail if more than $\pm 10\%$
<b>Test results shall be reported, classification is possible in case of exceeding the limits</b>	<b>Result to report</b>
PMT Non-linearity (by T-target in Type I CR Test Phantom)	Report if > 2%
Burn-In (high absorption object required)	Report if > 2%
Spatial Linearity (by spatial linearity image quality indicators in Type I CR Test Phantom)	< 2%
Imaging plate response variation (no test object required)	Report if > $\pm 10\%$
<b>Optional test on request</b>	<b>Result to report</b>
Imaging Plate Fading (no test object required), <i>optional test</i>	Report fading in %, calculated from values measured at 5 minutes and 2 hours.

Figure 3 shows the effect of SNR increase (equivalent to CNR increase) on the visibility of fine flaw indications [4, 5, 9]. The digitized fine grained film provides a SNR of 265 in the base material region. The DDA image was measured with a SNR of about 1500 and magnification of 3.5. It shows significantly finer flaw indications.



The qualification of DDAs is described in ASTM E 2597. The clause 10 of ASTM E 2597 on classification of DDAs is not really used by manufacturers and users yet. This may change with the next revision of ASTM E 2446, which considers iSR<sub>b</sub>-performance levels, which apply also for DDAs.

Some qualification parameters are different from the one of CR systems. The qualification of DDAs requires a special paragraph on the handling of differences in the performance of detector elements. This is clause 6 of ASTM E 2597: “Calibration and Bad Pixel Standardization”. The description of the different kinds of “bad pixels” enables its reliable qualification and description. The following “bad pixels” are described:

- Dead pixel - no response at all,
- Over responding pixels - greater than 1.3 times the median grey value of neighbours,
- Under responding pixels - 0.6 times the median grey value of neighbours,
- Noisy pixels - standard deviation in a sequence of measurements without radiation is more than six times the one of neighbours,
- Non-linear pixels - value exceeds a deviation of more than  $\pm 1$  % of the median value of neighbours,
- Persistence/Lag Pixels – changes the value in dependence on previous exposure,
- Bad neighbourhood pixels – cannot be distinguished from good pixels if neighbours are bad.

Most important is the definition for cluster kernel pixels (CKP), which cannot be sufficiently substituted by interpolation from good neighbourhood pixels (see also Fig. 4). The appearance of CKP can be a reason for rejection of detectors. All other “bad pixels” can be substituted by interpolation from neighbour pixels without significant effect on the images (see also [15]).

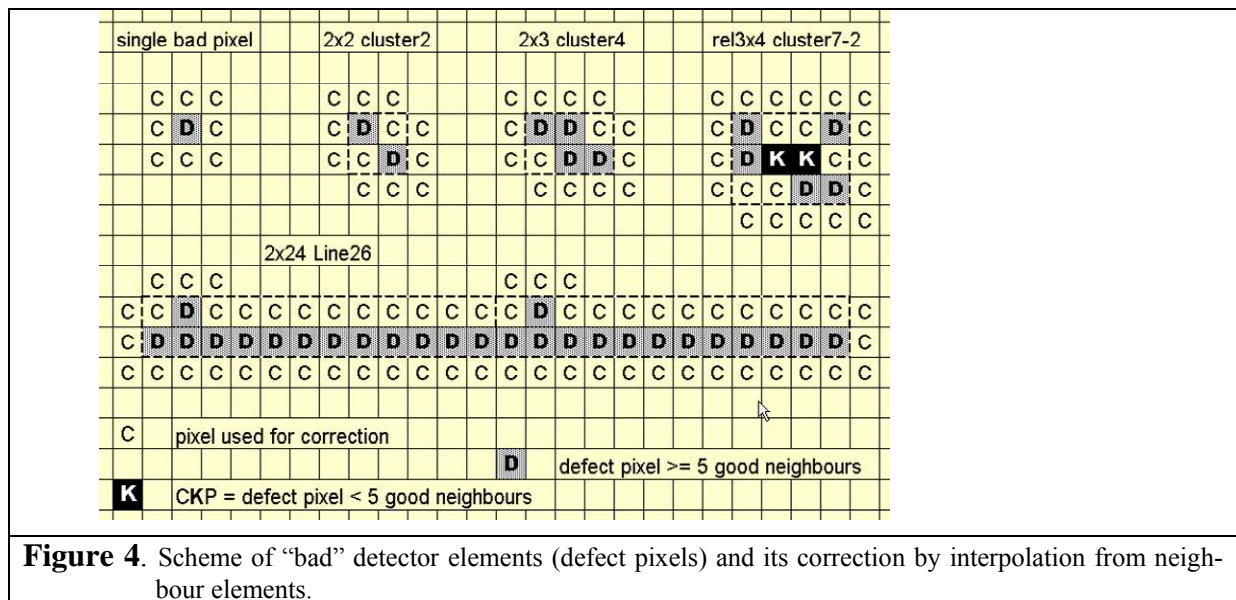


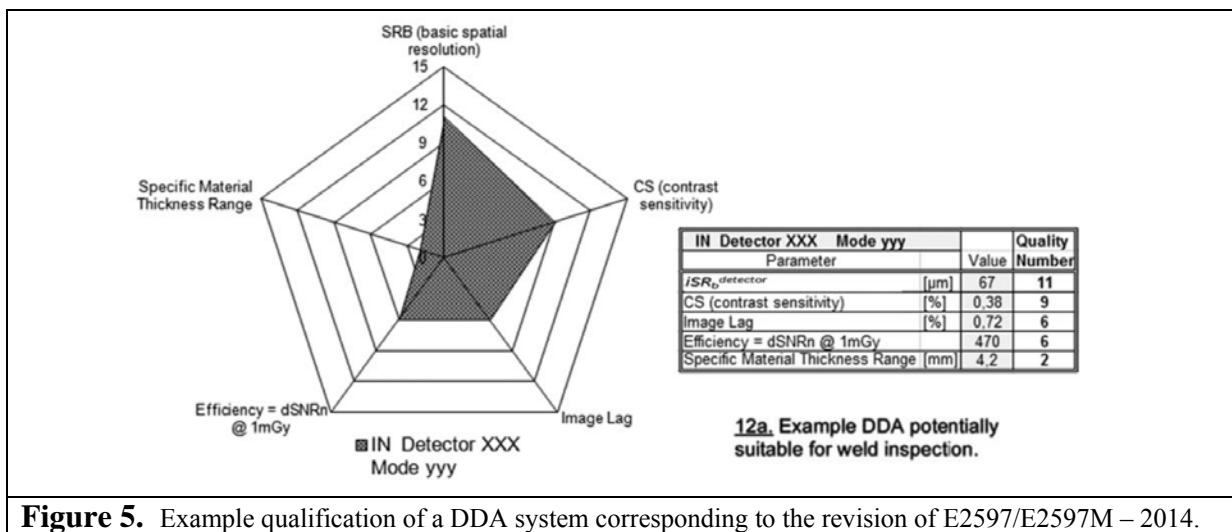
Figure 5 shows the spider net graph, which is an essential part of a DDA qualification report by the manufacturer. Two additional parameters are included in comparison to the CR qualification graph (Fig. 2).

**Image lag:**

This value is important when the detector is used for real time inspection (radioscopy) or with a high sequence of image acquisitions as typically required for computed tomography and serial part inspection. It provides information about the relaxation of the grey values of the detector elements with time (1 minute) after image exposure.

**Specific Material Thickness Range:**

It specifies the recommended material thickness range for application of the qualified detector. The thinner wall thickness is limited by 80 % of the maximum grey value of the DDA and the thicker wall thickness by a SNR of 130 for 2 % contrast sensitivity and SNR of 250 for 1 % contrast sensitivity.



**Figure 5.** Example qualification of a DDA system corresponding to the revision of E2597/E2597M – 2014.

Further parameters will be provided by the qualification report as:

- internal scatter radiation (ISR)—scattered radiation within the detector
- Burn in – provides information about permanent or long standing residual images of previous exposures, also called ghost images.
- Graphs for CS dependence on exposure and acquisition conditions and efficiency measurements and image lag decay.

**5. Hardware Requirements in Application Standards for Digital Radiography**

**5.1 Minimum Requirements**

All international radiographic standards regulate basically 4 major conditions to achieve a sufficient quality in radiographic testing as shown in Table 5.

**5.2 Unsharpness Requirements**

The application of digital detectors is mainly limited by the requirements on the maximum unsharpness. Standards for film radiography limit the geometrical unsharpness depending on source-object-detector distances and the source size only. The inherent unsharpness of NDT-films is low and negligible. Digital detectors can be applied only in contact with the object, if the inherent detector unsharpness is smaller than the permitted geometric unsharpness.

**Table 5.** Minimum requirements in industrial radiography

Requirement	Film	Digital	
	ISO, CEN, ASTM, ASME	ISO, CEN	ASTM, ASME, MAI
<b>Exposure</b>	Exceed minimum <b>optical density</b>	Exceed minimum required <b>SNR<sub>N</sub></b>	Exceed minimum required <b>CNR</b> for DDAs  CR systems shall be exposed to <b>EPS plateau</b> values (under discussion and published in MAI [2])
<b>Detector requirements</b>	Use required <b>film system class</b> or better	Use detectors, which achieve the required <b>SNR<sub>N</sub></b> and do not exceed <b>detector unsharpness</b> limits	Use detectors, which do not exceed <b>image unsharpness</b> limits
<b>Maximum image unsharpness</b>	Do not exceed the <b>geometrical unsharpness</b> limits	Do not exceed the <b>image unsharpness</b> limits	Do not exceed the <b>image unsharpness</b> limits
<b>Image quality</b>	Achieve the required <b>IQI contrast sensitivity</b>	Achieve the required <b>IQI contrast sensitivity and duplex wire resolution</b>	Achieve the required <b>IQI contrast sensitivity</b>

ISO 17636-2 permits the application of digital detectors which have an inherent unsharpness close to the permitted geometric unsharpness values of film radiography (ISO 17636-1). The geometric unsharpness limits are the same in ISO 17636-1 and ISO 17636-2. Figure 6 shows the permitted unsharpness values of table B.13, B.14 in comparison to the permitted geometrical unsharpness of film radiography. The user may chose a high resolution detector and use a larger spot size and a short SDD or a detector with less resolution and may need a mini or micro focus tube for the same inspection task. Magnification technique may be used to optimize the application. ISO 17636-2 provides the following formula for calculation of the image unsharpness ( $2 \cdot SR_b^{\text{image}}$ ) as required by tables B.13 and B.14 of ISO 17636-2:

$$U_{\text{Im}} = \frac{1}{v} \cdot \sqrt{U_G^2 + (2 \cdot SR_b^{\text{detector}})^2} \quad (2)$$

with

- $U_{\text{Im}}$  – Image unsharpness
- $v$  – Magnification
- $U_G$  – Geometric unsharpness at detector
- $SR_b^{\text{detector}}$  – Basic spatial detector resolution
- $U_{\text{Detector}}$  - inherent unsharpness of detector ( $U_{\text{Detector}} = 2 \cdot SR_b^{\text{detector}}$ ).

The geometric unsharpness  $U_G$  at the detector is calculated by:

$$U_G = \left( \frac{SDD}{f} - 1 \right) \cdot d \quad (3)$$

with

- $SDD$  – Source –to–detector distance
- $f$  - Source-to-object distance
- $d$  – Source size.

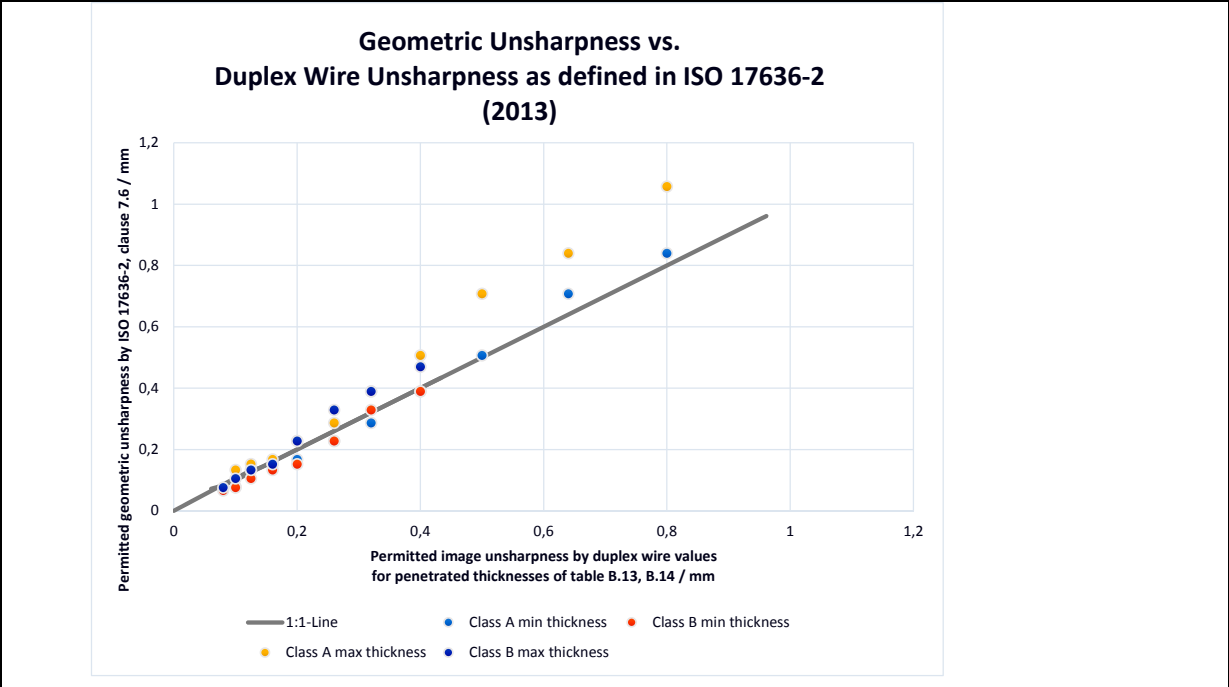
ASTM E2698-10 “Practice for Radiological Examination Using DDAs” provides a similar formula as eq. (2).

All international NDT standards do not regulate film unsharpness requirements and limit the permitted geometric unsharpness in dependence on the material thickness only. The inherent unsharpness of digital detector arrays are limited by the pixel size and the radiation converter material. Detectors with large pixel size are very efficient, in comparison to high resolution detectors. User prefer the application of highly efficient detectors, but they have to consider the risk of missed fine indications.

The limits of the permitted geometric and/or image unsharpness values vary in the different international standards significantly. Table 6 provides an overview about the different unsharpness limits of selected standards and provides the corresponding duplex wire values for user qualification.

ISO 17636-1 and -2 were adopted as European standards under EN ISO 17636-1, -2 in 2013 and substitute the old EN 1435 and ISO 17636 (2003). Figure 7 shows the basic differences. ISO 17636 (2013) and ASTM E 1030 (2004) provide unsharpness limits by a formula.

ASTM E 1030 (2004) required an unsharpness limit of 1% of the material thickness and a contrast sensitivity (EPS) of 2% of the material thickness (2-2T). All other ASTM (also ASME BPVC Section V, Article 2) standards define unsharpness limits by tables for a given thickness range (step functions, see Fig. 7). One specific feature of ISO and European RT standards is the definition of an enhanced testing class B, which basically requires 1/2 of the unsharpness limits of the standard testing class A. ISO 17636 (part-1 and -2), class A, and ASME BPVC Section V, Article 2, ASTM E 1742, E 2104 and the MAI guideline [2] are comparable in the requirements. The authors see some critical issues in the testing quality for ASME BPVC Section V, Article 2 and ASTM E 1742, because no differentiation is made for material thicknesses below 5 cm (2 inches). Changes are recommended to adapt the state of the art in RT of thinner materials testing as considered in the other mentioned standards.



**Figure 6.** Comparison of permitted geometrical unsharpness and duplex wire unsharpness of ISO 17636-2.

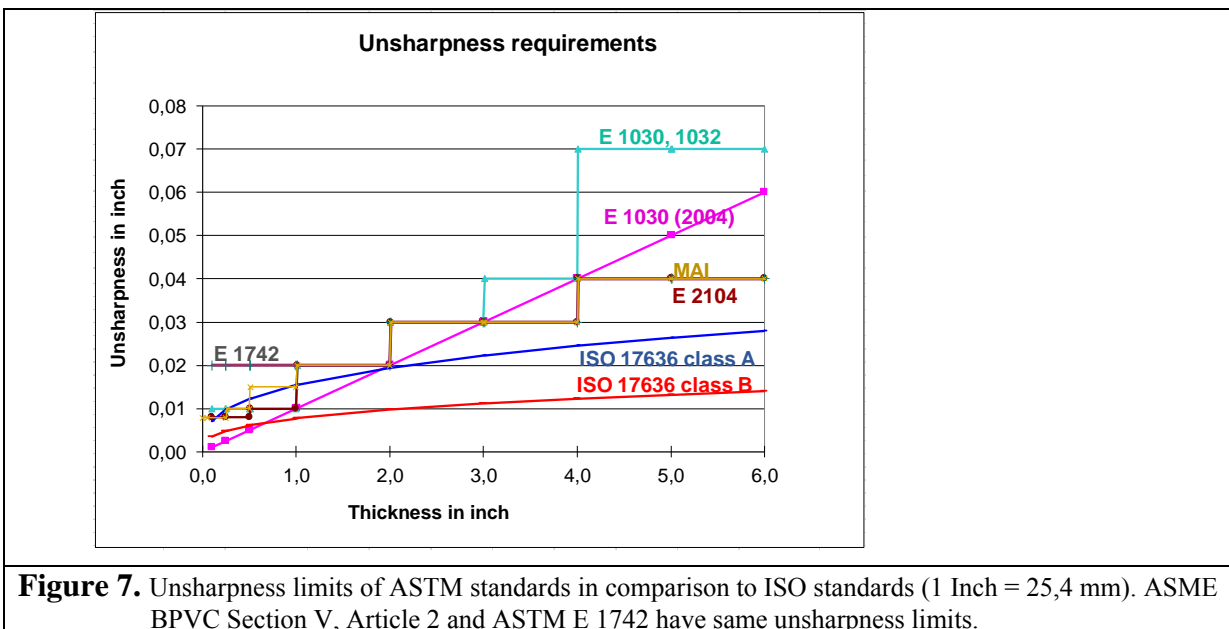
Significantly higher unsharpness limits are permitted for corrosion and wall thickness measurements. EN 16407, published in 2014, limits the geometric unsharpness to 0.3 mm for class B testing and to 0.6 mm for class A testing (standard quality).

**Table 6.** Unsharpness limits in different standards and standard drafts and the corresponding duplex wire requirements.

Material thickness in mm	Material thickness in inch	MAI guideline 2-2T, 2011, WK30625		ASTM E 1030, 2004 (1%)		ASTM E 1030, ASME SE 1030		ASTM E 2698		ASTM E 2104		EN 17636-2, Tab B.13, pr EN 12681-2, Class A		EN 17636-2, Tab B.14 pr EN 12681-2, Class B		EN 13068-3, Class B	
		U <sub>lim</sub> / Ug in mm	Duplex Wire value	U <sub>lim</sub> / Ug in mm	Duplex Wire value	U <sub>lim</sub> / Ug in mm	Duplex Wire value	U <sub>lim</sub> / Ug in mm	Duplex Wire value	U <sub>lim</sub> / Ug in mm	Duplex Wire value	U <sub>lim</sub> / Ug in mm	Duplex Wire value	U <sub>lim</sub> / Ug in mm	Duplex Wire value	U <sub>lim</sub> / Ug in mm	Duplex Wire value
6	1/4	0,203	D10	0,06	D13+	0,254	D10	0,254	D10	0,203	D10	0,242	D9	0,121	D12	0,20	D10
12	1/2	0,239	D10	0,12	D13	0,254	D10	0,254	D10	0,254	D10	0,305	D8	0,151	D11	0,26	D9
25	1	0,381	D8	0,25	D10	0,508	D6	0,508	D6	0,508	D6	0,389	D7	0,195	D10	0,26	D9
50	2	0,762	D5	0,50	D6	0,762	D5	0,762	D5	0,762	D4	0,491	D7	0,245	D9	0,26	D9
100	4	1,016	D3	1,00	D3	1,778	D1	1,016	D3	1,016	D3	0,617	D6	0,308	D9	0,26	D9

## 6. Image Quality and Compensation Principles of ISO 17636-2

The evaluation of the image quality in industrial radiography has been based on the visibility of wires and hole type IQIs on films since decades. The basics of the perception of small indications by human operators can be traced back to papers of Rose on the image quality of images taken with optical cameras [16 - 20]. It was pointed out already in the first papers that the human eye can be treated in a similar way than a camera due to its construction.



**Figure 7.** Unsharpness limits of ASTM standards in comparison to ISO standards (1 Inch = 25,4 mm). ASME BPVC Section V, Article 2 and ASTM E 1742 have same unsharpness limits.

It was concluded that all human operators have almost the same perception threshold (PT) for small circular indications (e.g. pores) which can be determined from an image of just visible indications as e.g. described in ASTM E 746 for EPS performance measurements. The PT is approximated from the product of the indication diameter and the normalized CNR:

$$PT = d^{hole} \cdot \frac{CNR}{SR_b^{image}} \quad (4)$$

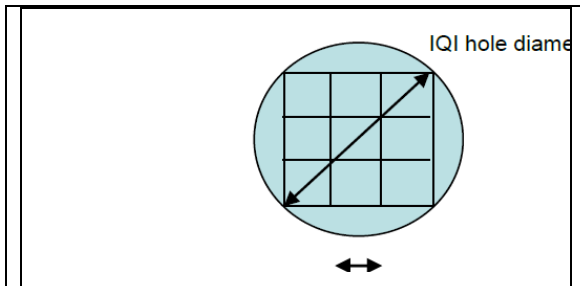
The standard ASTM E 746 describes hole plate IQIs which are suitable to determine the PT. If 20 of 30 holes can be seen the value PT is about  $PT \approx 10$ . For clear visibility of the holes in the hole type IQIs the threshold may be increased further up to  $PT = 12$ . Studies of the ASTM E 07 committee for preparation of the DDA practice ASTM E 2698 and MAI guideline [2] concluded that a 2-2T hole is just visible if  $PT = 10.6$ . This applies for the resolution criterion of the MAI guideline as shown in Fig. 8. The value is also partly published in the DDA practice ASTM E 2698. This standard requires a  $CNR \geq 2.5$  in a 4T hole and concludes that the 2T hole is then clearly visible.

Background information on the visibility of IQIs was published in [4, 5]. Finally the formula for safe detection of a 2T hole was determined with  $CNR_{min} = 2.5$  by a Boeing study for the ratio of hole diameter to basic spatial resolution of  $d_{hole}/SR_b^{image} = 4.25$  as shown in Fig. 8. The correct formula for determination of the minimum  $CNR_{min}^{hole}$  for the visibility of a related IQI hole is:

$$CNR_{min}^{hole} = \frac{11 \cdot SR_b^{image}}{d_{hole}} \quad (5).$$

BAM determined a similar value in internal trials, which was 10 instead of 11.

Most European users apply wire IQIs instead of hole type IQIs. The PT values for wires are smaller. Smaller wires can be seen as compared to hole type IQIs. In old trials a factor of 2.5 is given for the wire visibility, which means that 1T hole indications need to be 2.5 times larger in the diameter than wires for 1T holes. This is not entirely correct. First trials have shown that the conversion is more complicated. The following formula can be derived from the paper [5] and ASTM E 747 for calculation of  $CNR_{min}^{wire}$ :



**Figure 8.**

MAI requirement of detector resolution for the visibility of an IQI hole. The effective pixel size of digital image ( $SR_b^{image}$ ) shall be the hole diameter  $d_{hole}$  divided by 4.25. 3 x 3 times effective pixels ( $SR_b^{image}$ ) shall be in the 2T hole image if 2-2T is required.

$$CNR_{min}^{wire} = \frac{PT_{wire} \cdot SR_b^{image}}{d_{wire}^{3/2}} \quad (6).$$

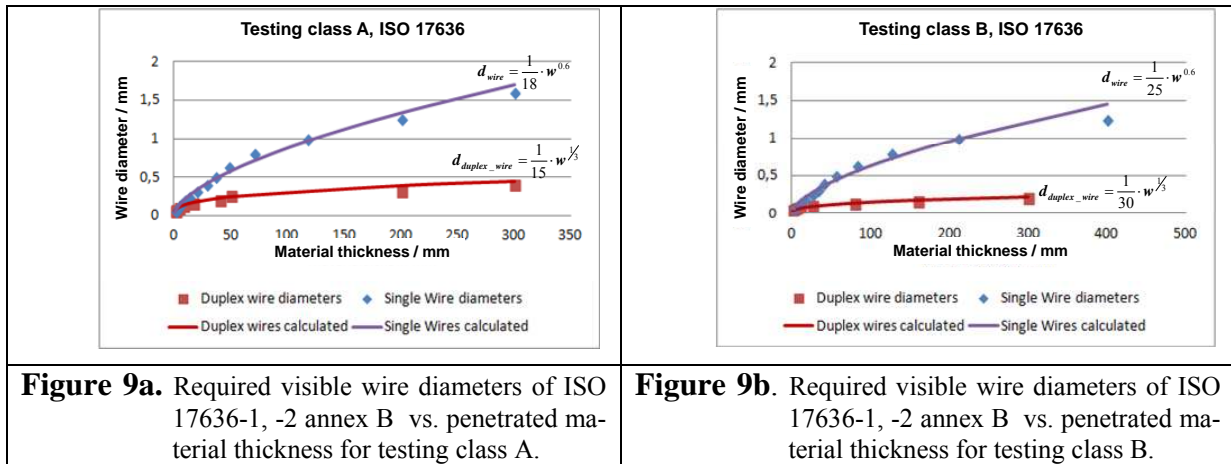
Eq (5) provides a  $CNR_{min}^{hole}$  value which is independent from the IQI thickness. It is just a numerical tool to help the image interpreter to decide if the image quality of a digital radiograph can be accepted.

Eq (6) seems to be too complicated for users. Further verification trials are required, since the equation was derived from visual film evaluation trials in dark rooms. The discussed integrating effect of the human eye along the wire length (if  $l > 0.7$  mm) seems to vary at different

zoom factors. No attempt has been undertaken to provide related values for standards. No exact value is known for  $PT_{wire}$  yet. The estimated value is  $PT_{wire} = 0.3 \dots 1$ . Users are still evaluating the wires visually at the monitor. Since operators can see wires at  $CNR < 1$  and wires are not exactly parallel, it is complicated to determine the reliable  $PT_{wire}$  value for evaluation of wire visibility. Also aliasing effects appear, if the wires are in the order of the pixel size of the digital detector array.



Consequently, it cannot be expected that the thickness contrast sensitivity is a constant value as many ASTM standards require (e.g. 2-2T). Fig. 1 shows that ISO 19232-3 and ASME BPVC Section V Article 2 require material thickness dependent contrast sensitivities as consequence of experiences collected over decades. The IQI contrast sensitivity (EPS) improves with the negative square root of the penetrated material thickness [4, 5]. Figure 9 shows the increase of the required wire diameters with material thickness to inspect. The required wire diameters increase with thickness power 0.6 and consequently the thickness contrast sensitivity improves with material thickness power -0.4 (see Fig. 1 of [5]). This indicates that the differences in the visibility of wires and holes depend differently from CNR and  $SR_b^{\text{image}}$ . Figure 9 shows that the required wire diameters in class B are smaller by square root of 1.9 than the diameters of the wires in class A, which can be mainly related to the required reduction of  $SR_b^{\text{image}}$  by a factor of 2 from class A to class B requirements.



## 7. Summary

International standards (Tab. 1) for film radiography and digital radiography were analysed to compare the required contrast sensitivity values as shown in figure 1 and the permitted unsharpness values as presented in Tab. 6 and Fig. 7. The standards provide contrast sensitivity requirements by IQI visibility values and geometric or image unsharpness limits. ASME Sec. V Art. 2, ISO 19232-3 and ISO 17636-1 and -2 provide tables with minimum visibility values for hole type and wire type IQIs. The values for the hole type IQIs decrease (become better) with the inverse square root of the material thickness. The selection of the right digital detector is essential for its standard conform application. The key parameter for the standard conform selection of a digital detector is its basic spatial resolution. CR systems are currently available with  $SR_b^{\text{detector}}$  values between 0.04 and 0.16 mm. DDAs are currently available with  $SR_b^{\text{detector}}$  values between 0.08 and 0.4 mm. The standard ISO 17636-2 requires in tables B.13 and B.14 digital detectors with  $SR_b^{\text{detector}}$  values between 0.04 and 0.4 mm. All US standards permit the application of DDAs with  $SR_b^{\text{detector}} > 0.1$  mm, which are available now. Users of old DDAs with higher  $SR_b^{\text{detector}}$  may use the compensation principle II [15] of ISO 17636-2 or use magnification technique. New qualification standards are under development for CR systems, because all qualified systems achieve the highest classification. New performance levels are under development, which consider limits for the achievable  $SNR_N$ ,  $SR_b^{\text{detector}}$  and EPS values. The requirement of ASTM E 2698 and of the MAI guideline [2] for the visibility of IQI holes with  $CNR_{\text{min}} = 2.5$  has been improved by a formula, considering additionally the ratio of IQI hole diameter and  $SR_b^{\text{image}}$ . A corresponding formula was derived for the prediction of wire visibility. This formula needs further trails in different labs.

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