

## A COMPARATIVE STUDY ON THE PERFORMANCE OF DIGITAL DETECTOR SYSTEMS FOR HIGH ENERGY APPLICATIONS

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### Abstract

For cast components reaching or exceeding total material thicknesses of 150mm, high energy sources such as linear accelerators or Betatrons are required in order to obtain reasonable exposure times. In this study, the performance of digital detector systems, involving imaging plates (IP) and digital detector arrays (DDA), was evaluated with respect to the testing class B requirements as formulated in the standard EN ISO 17636-2. As a reference, traditional radiographic film and a Cobalt-60 source was used. With film exposures, testing class B was achieved with Co-60 and Betatron (7.5 MV) at longer exposure times. The preliminary results show that the testing class B was not obtained with the examined digital detector arrays (DDA) and the high resolution imaging plates (IP), even at 40, 60 and 80 minutes exposure time with a 7.5 MV Betatron. Class A was achieved using high resolution imaging plates with optimized metal filters between object and IPs and a high resolution DDA with intermediate Cu filters. Class A was also achieved applying a DDA with lower basic spatial resolution than required by Table B.13 of EN ISO 17636-2, but using the compensation principle as described in this standard. The next generation of digital detector arrays might potentially be able to obtain class B performance with the expected spatial resolution and sensitivity improvements.

**Keywords:** Radiography, Betatron, digital detector array (DDA), casting; image quality, standards

## 1. Introduction

Radiographic inspection of critical components with high material thickness (150 mm and more) requires high energy sources and rather long exposure times. Digital radiography with digital detector arrays and imaging plates hold the promise of a notable decrease in exposure time and enhanced image quality because of their increased sensitivity with respect to traditional industrial X-ray films. At the same time, the significantly larger dynamic range should improve robustness in terms of the useable incident radiation dose range. The objective of this study was to investigate the performance of digital detectors representative of the state-of-the-art in 2013 with realistic double-wall inspection configurations using high energy radiation sources.

The chosen configuration is representative of the inspection of an elbow pipe with an outer diameter of 907 mm. The elbow pipe is represented by two planar mock-ups with 70 mm and 81 mm wall thickness. The digital detectors used in this study are an imaging plate (IP) with a basic spatial resolution of 40  $\mu\text{m}$ , scanned with 50  $\mu\text{m}$  pixel size, and two digital detector arrays with respective pixel sizes of 200  $\mu\text{m}$  and 143  $\mu\text{m}$ . The X-ray source used was a Betatron with a maximum energy of 7.5 MeV and a dose rate of 5.3 R/min (53 mGy/min) at a distance of 1 meter. The reference image was obtained on a traditional C3 X-ray film system, in conjunction with a Co 60 source. Figure 1 shows the installation during a Betatron exposure with a digital detector array (DDA).

## 2. EN ISO 17636-2 standard requirements

For this application, the requirements were to achieve the image quality according to testing class B as described in the new EN ISO 17636-2 standard for weld testing using digital detectors [1]. According to this standard, which replaced the older EN1435 standard in May 2013 for digital radiography applications, a wire-type image quality indicator (IQI) with element number W8 (0.63 mm wire diameter) shall be visible (IQI positioned on the detector side) for the given penetrated thickness. The associated basic spatial resolution shall be at least 0.13mm (for a DDA or IP), which requires duplex wire IQI D9.

The EN ISO 17636-2 standard describes the compensation principle (II), which allows to compensate the underperformance on basic spatial resolution (missing duplex wire pairs) by an increase of the contrast sensitivity (better single wire IQI detection), but only up to a certain point.



**Figure 1.** Preparation of experimental setup with DDA and Betatron

### 3. Experimental Results and Discussion

The Table 1 summarizes the experimental conditions of the various exposures and the obtained results using industrial X-ray films and imaging plates. The column “wire IQI” indicates the just visual wire number value in the IQI set “W6 FE-EN” (EN ISO 19232-1). The main parameters in Table 1 are the exposure time ( $t_{exp}$ ), source-to-detector distance (SDD), geometrical unsharpness  $U_g$ , optical density o.D. of NDT films or signal-to-noise ratio (SNR) for digital detector images, as well as the IQI value seen.

For an image quality according to the standard EN ISO 17636 requires a wire IQI visibility of W6 for testing class A and W8 for testing class B. The results show that all exposures with NDT films satisfy the requirements of class B, as expected using longer exposure times. Film packages of two films were exposed synchronously to an optical density o.D.  $> 1.3$ . The films were evaluated under double film viewing condition. The usage of single films and single film viewing would require the double exposure time as given in Table 1.

For exposures with imaging plates, the testing class A was achieved only with optimum detector front screen packages and back-scatter filters. For a full appreciation of the image quality, the normalised signal-to-noise ratio ( $SNR_N$ ) is necessary, for which the “basic spatial resolution” must be known [2]. It is typically obtained using a duplex wire IQI.

Unfortunately the duplex wire IQI of EN ISO 19232-5 was not visible in IP radiographs of the high thickness materials. Therefore, the unnormalized SNR values are given in Table 1.

The Co-60 source used for these experiments had an activity of 30 Ci, with a focal spot size of  $4 \times 4.2 \text{ mm}^2$ . The dose rate measured at a distance of 1 meter was about 393 mGy/h. The Betatron was used with its maximum energy of 7.5 MeV, with a focal spot measured to be  $1.5 \times 3 \text{ mm}^2$  (own measurements, according to the data sheet, the focal spot should be smaller). The dose rate observed at a distance of 1 meter was 53 mGy/min (3180 mGy/h). The exposure time with the Betatron is limited to 40 minutes, since the device requires a cool-down period of 15 minutes after 40 minutes of use.

**Table 1. Results with X-ray films and imaging plates**

Source	Detector	$t_{\text{exp}}$	SDD / $U_g$	o.D. <sup>1</sup> / SNR	Wire IQI	Comments
Co60	Film C3 <sup>2</sup>	9h	1000 mm / 0.4 mm	3.25	W9 0.5 mm	Vacupac 2 x 0.027 $\mu\text{m}$ Pb, 0.5 mm Fe filter intermediate Lower unsharpness than Betatron radiographs
Beta	Film C3 <sup>2</sup>	45min	1300 mm / 0.2 mm	3.20	W8 0.63mm	Vacupac 2 x 0.027 $\mu\text{m}$ Pb, 0.5 mm Fe filter intermediate 12 times shorter exposure time than Co-60 exposure
Beta	Film C3 <sup>2</sup>	30min	1300 mm / 0.2 mm	2.2	W7 0.80 mm	W8 barely visible
Beta	IP HR	60min	1300 mm / 0.2 mm	350	W5 1.25 mm	IP HR 50 $\mu\text{m}$ 35x43cm <sup>2</sup> , grey level: 8500, filter: 2 mm Pb + 1mm Sn + 1mm Cu
Beta	IP HR	60min	1300mm / 0.2 mm	375	W6 1 mm	IP HR 50 $\mu\text{m}$ 35x43cm <sup>2</sup> , grey level: 8500, filter: 1 mm Pb, + 1mm Cu + 1mm Sn

<sup>1</sup>optical density (o.D.)

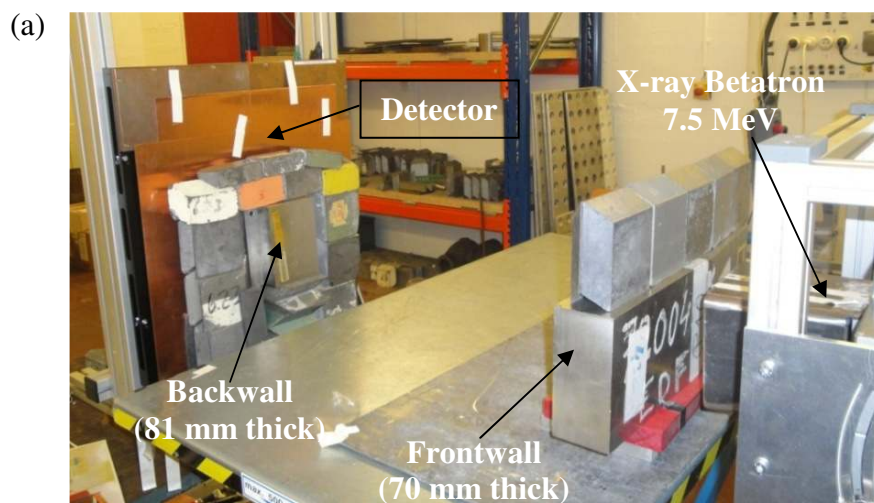
<sup>2</sup>double film exposure and double film viewing

The IP UR1 detector is an IP with low intrinsic unsharpness and high basic spatial resolution at low energies (down to 40  $\mu\text{m}$ ), but low sensitivity. The experiments clearly show that the best results were obtained with C3 film and a Co-60 source using 9 h exposure time with double film exposure. Replacing the Co-60 source with a Betatron for the film experiment allows to reduce the exposure time by a factor of approx. 12 (normalized to the SDD: factor 14), which is larger than expected from the exposure dose comparison (factor 8). On the other hand, the combination Betatron and HR imaging plates did not allow a significant decrease of exposure time with respect to the NDT film systems. The two experiments with imaging plates further show that the right choice of the filter allows to gain one IQI wire value. For the experiments with imaging plates, interpretation of the results was done with and without image processing (high pass filtering), but without a notable difference.

The experimental setup for inspecting thick-walled cast component using the high-energy Betatron and digital detector arrays is shown in Figure 2. The geometric set up (SDD and SOD) was the same as for film and IP inspection as shown in Figure 1 and Table 1. The signal-to-noise ratio in the image has been enhanced by performing optimum detector calibration (i.e. effective bad pixel correction and compensation of structure noise of the detector elements). Additionally, an optimum shielding was employed in order to reduce the influence of scattered radiation from surroundings on image quality (see Fig. 2). The results achieved using two different digital detector arrays at various exposure times are summarized in Table 2. For the experiments with the DDAs it is necessary to verify if the spatial resolution is compatible with the requirements of the EN ISO 17636-2 standard since the detector pixel size is significantly larger than the basic spatial resolution of film and IP radiographs. A series of dedicated experiments were conducted with duplex wire IQIs to obtain this quantitative information. In order to evaluate the basic spatial resolution of digital images of the thick-walled component, a CERL C duplex plate IQI was used as well as a duplex wire IQI according to EN ISO 19232-5.

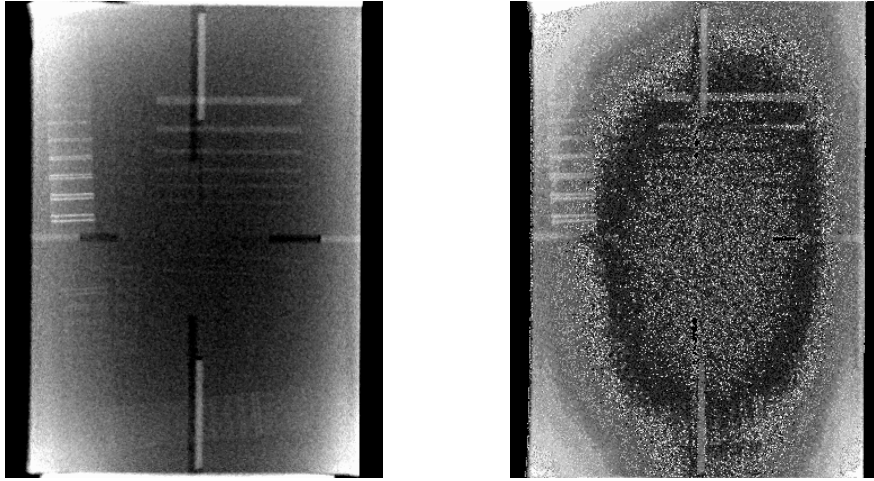
Detector A has a pixel size of 200  $\mu\text{m}$  and a thick Gadox-Scintillator PI-100 and allowed to distinguish duplex wire D4 only. Applying the compensation principle, as permitted by the standard, inspection class A was achieved with an exposure time of 40 minutes, but the testing class B was not achievable with this detector due to its insufficient basic spatial resolution. It should be mentioned, that the required wire resolution was proven at 40 minutes exposure time corresponding to Table B.9. The image quality for class B testing was confirmed in relation to EN 1435, but not corresponding to EN ISO 17636-2.

Detector B (pixel size 143  $\mu\text{m}$ , basic spatial resolution 160  $\mu\text{m}$  (Duplex wire D7 achieved) and thin Gadox-Szintillator DRZ Standard) satisfies the requirements of testing class A without resorting to the compensation principle at 20 minutes exposure time, and almost achieved class B (still 2 more wires to be detected) after increasing the exposure time by a factor of 4. A 4 mm copper detector front filter was used to increase the contrast-to-noise ratio (CNR) in the digital image (result of the reduction of scattered radiation detected by DDA).



(b)

(c)



**Figure 2.** (a) Experimental setup showing front wall and back wall of the cast component inspected using 7.5 MeV X-ray Betatron and a digital detector array (pixel size 200 $\mu$ m). Measured digital X-ray image with (b) 20 min, (c) 40 min exposure times.

**Table 2. Results with high-resolution digital detector arrays (DDAs)**

Matrix Detector Type (exposure time)	SR <sub>b</sub> (mm)	SNR <sub>N</sub>	Wire Type IQI	CERL C Duplex Plate IQI	ISO 17636-2 Required class A Wire /duplex IQI
A (20 min)	0.4	120	W7 0.8 mm	D4	W6 / D6
A (40 min)	0.4	145	W9 0.5 mm	D4	W6 / D6
B (20 min)	0.2	144	W6 1 mm	D7	W6 / D6
B (40 min)	0.2	175	W6 1 mm	D7	W6 / D6
B (80 min)	0.2	275	W7 0.8 mm	D7	W6 / D6

SR<sub>b</sub>: Basic spatial resolution of image

## 4. Conclusions

The results certainly show that industrial NDT films remain ahead of digital detectors in terms of its image quality for inspections at high penetrated steel thicknesses. The exposure times of NDT films in double film exposure and double film viewing technique was comparable to the exposure times used for the digital detectors. Inspection class A was obtained with imaging plates and digital detector arrays using a Betatron as high energy X-ray source (7.5 MeV). For these applications, a serious decrease in exposure time was observed in comparison to Co-60 exposures. Testing class A was achieved with imaging plates only if suitable packages of metal filters were used in front of the IP cassette and with good back scatter filtering.

The advantage of NDT film image quality as compared to imaging plates and DDAs may be explained by the lower sensitivity for scattered radiation of the radiographic film. This improves the contrast-to-noise ratio (CNR) of the film images in comparison with the CNR of the radiographs taken with imaging plates or DDAs. Especially for DDAs the filters in front and behind the detection layer need to be improved, whereas for imaging plates suitable filter combinations are given in EN ISO 17636-2. It should be possible to obtain testing class B with a DDA with improved basic spatial resolution and specialized internal screens as e.g. thick crystalline CsI screens. Currently, direct converting detectors with 100  $\mu\text{m}$  pixel size and 750 – 2000  $\mu\text{m}$  detection layer of CdTe are available, which are up to now used with success for testing class B up to 300 keV. It will require more internal shielding of the electronics to apply them at 7.5 MeV to improve the results shown here.

## References

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