A REVIEW OF DIGITAL RADIOGRAPHY TECHNOLOGY FOR VALVE INSPECTION

K. Stoev, F.M. Guérout, D. Horn

AECL – Chalk River Laboratories
Inspection, Monitoring and Dynamics Branch
Chalk River, Ontario, Canada, K0J 1J0

Abstract

There are thousands of valves in a nuclear power plant (NPP) used for control, safety and checks in various plant systems, so there is a well-identified need for fast and reliable inspection and diagnostics of valves. Digital radiography can provide considerable improvements to the inspection and testing procedures for valves in comparison to classical film radiography. These improvements can lead to significant financial advantages by providing real-time inspection results, significantly reduced inspection and decision-making time, and reduced operational cost. Digital image processing, including digital image enhancement, digital archiving, and digital communication of the images and the results, is also a considerable advantage over classical film radiography technology. Another advantage of digital radiography technology is the improved safety and the reduced environmental impact due to reduced exposure/test times, use of smaller exclusion zones, elimination of chemical processing, and absence of disposable materials.

This paper reviews the existing technology and evaluates the potential of digital radiography for inspection and diagnostics of valves. Station needs and requirements are assessed, and the safety, environmental and economical constraints of digital radiography techniques estimated. The advantages and disadvantages of different digital radiography equipment are compared, and their limitations and characteristics studied.

1. INTRODUCTION

The ever-increasing safety requirements of the nuclear industry are among the main forces behind the fast development of non-destructive examination (NDE) techniques. There are thousands of valves in a nuclear power plant (NPP) that are used for control, safety and monitoring in the Heat Transport System, Moderator System, Steam Generator System, Reactor Regulating System, and Safety System. It is very important to have reliable inspection tools that can be used for proper assessment of the state of the valves. It is of interest to the nuclear industry to evaluate the applicability of different versions of industrial radiography for inspection and monitoring of valves in NPPs. The stations' personnel need radiography to complement results obtained via other inspection techniques.

This paper focuses on the applicability of digital radiography (DR) to inspection of the valves in NPPs, and on the different benefits of such inspections, such as cost, time savings and improved safety. Measurements performed at Chalk River Laboratory with two different digital radiography systems are presented and discussed.

2. ASSESSMENT OF THE REQUIREMENTS FOR VALVE RADIOGRAPHY

2.1 Types of Valves

Stations have thousands of valves with different types and sizes, and most of these valves need regular monitoring and maintenance. The most common types of valves in NPPs are:

- Check valves.
- Ball valves.
- Butterfly valves.
- Gate valves.
- Globe/Plug valves.

In order to evaluate the applicability of digital radiography, it is necessary to collect the following types of information about the valves:

- Sizes of the valves.
- Typical average wall thickness.
- Maximal material thickness including internal parts.
- Valve material.

A small sample of the valves used in a CANDU station is presented in Table 1.

Table 1
Examples of Valve Types

Valve Number	System	Size ["]	Port Size ["]	Material	Fluid	Max. Wall Thickness ["/mm]	Weight [lbs]
V20	Gland Seal Circuit	2	1.68	SS	D_2O	0.76/19.3	55
V45	Liquid Zone Control Supply Circuit	2	2.00	SS	D_2O/H_2O	1.00/25.4	32
V105	Emergency Core Cooling/Recovery	2	2.25	CS	H_2O	1.00/25.4	50
V14	D_2O Supply	2 1/2	2.00	SS	D_2O	1.00/25.4	50
V1	Breathing Air	2 1/2	2.50	SS	Air	1.00/25.4	36
V49	Emergency Water Supply	3	2.62	CS	H_2O	1.28/32.5	105
V10	D_2O Feed and Bleed	3	2.62	CS	D_2O	1.30/33.0	105
V3	D_2O Feed and Bleed	3	2.62	CS	D_2O	1.30/33.0	110
V12	Coolant Storage/Transfer/Recovery	4	3.44	CS	D_2O	1.50/38.1	158
V223	Instrument Air	4	3.44	SS	Air	1.70/43.2	150
V301	Supply Circuit (Water Systems)	4		SS	H_2O	1.00/25.4	100
V24	Purification Circuit	6	5.19	CS	D_2O	2.60/66.0	520
V15	Supply Circuit (Water Systems)	6	6.00	CS	H_2O	2.00/50.8	166
V28	Shield Cooling Circuit	10	7.62	CS	H_2O	2.91/73.9	141
V33	Emergency Core Cooling/Recovery	12	10.00	CS	D_2O/H_2O	4.30/109.2	2900
V1	Main Feedwater Circuit	12	11.34	CS	H_2O	2.30/58.4	2600
V3	Moderator	14	12.12	SS	D_2O	2.10/53.3	1400
V4	Emergency Core Cooling/Recovery	16	12.50	CS	D_2O/H_2O	4.31/109.5	545

As can be seen, there is a large variety in the types and sizes of the valves that need to be monitored and inspected. It should be noted that the total material thickness could be significantly greater than the maximum wall thickness presented in Table 1. This makes the radiography of valves especially challenging, since very different thicknesses need to be radiographed simultaneously.

2.2 Possible Areas of Application of DR

Generally speaking, the possible applications of digital radiography for valve monitoring and inspection can be classified as follows:

- Determining position of internal parts in valves (like the flapper in check valves, hinge pins, hinge arms, seats, discs, disc nut pins, etc.)
- Orifice profiling.
- Determining dimensions (angles, shape, spacing, etc.) of valve parts.
- Locating foreign objects inside valves.
- General examination and inspection of wear of valve internals (like hinge pins, hinge arms, seats, discs, disc nut pins, etc.)
- Detection of leaking valves.
- Detection of deformations, liquid level, direction of liquid flow, etc.
- Weld characterization in valves.
- Evaluating the degree of corrosion/erosion, or other types of wall thinning, like FAC (flow accelerated corrosion) in valves.
- Determination of the amount of deposition in valves and orifices.
- Detection of cracks in valves.

For example, check valves automatically open when the flow is in the desired direction and seal when flow is in the opposite direction. Possible applications of digital radiography for check valve monitoring could include: (i) to determine the location of the disc in the check valve; (ii) to detect seat wear; (iii) to detect leakage; (iv) to detect hinge pin wear.

2.3 Test Environment

It is anticipated that the digital radiography system will be used mainly during shutdown and maintenance periods. In this case, the equipment and personnel will be subjected to conditions similar to those in a radiography lab: ambient temperature, atmospheric pressure, and lower background radiation. In some cases, the digital radiography system will be used during normal operation of the plant, which could mean higher temperatures and/or higher background radiation. These conditions have to be taken into account when considering the applicability of different DR systems, and the following questions have to be answered before selecting a portable DR system:

- Are the valves empty or filled with liquid?
- What is the level of the radiation background at the test site?
- Are the valves (or other test objects) located in accessible areas?
- Are there moving parts inside the valves during the test?
- What is the level of vibration at the valve inspection site?
- What is the temperature at the valve inspection site? Some detectors have temperature-sensitive performance.
- Is it expected that the DR system be used in a wet environment or subjected to water?
- Is it expected that all tests are done inside the NPP building(s)?

- What are the portability requirements, i.e., is the system to be operated by one person only?

2.4 Testing Capacity Throughput Requirements

It is important to estimate the total number of radiographs per year to be performed and to specify the test speed requirements. For example, are there cases where immediate results are needed? In order to evaluate the throughput requirements correctly, the following information has to be collected:

- Total number of valves to be tested per year.
- How fast the results from the radiography are required.
- Other tasks to which the DR system will be applied.

2.5 Safety and Code Requirements

The need for evacuation of the personnel from the exclusion zone, and/or for the removal of equipment or parts of other systems, has to be evaluated on a case-by-case basis. In all cases, the exclusion zone has to be adjusted as per station radiation safety procedures and corresponding ALARA requirements. For any specific case, there will be a requirement to set an exclusion zone based on radiation exposure limits for the general public (i.e., 0.1 mrem/h or 0.1 rem/year), or for nuclear energy worker (NEW) requirements (i.e., 1 mrem/h or 2 rem/year). In addition, depending on the accessibility of the tested valves and the practicality for each specific case, shielding should be considered for further reduction in the exposure rate and exclusion zone, especially when a large exclusion zone is needed but is not practical for other reasons. Provision should be made in the testing procedure to periodically inspect the condition of the radiation sources and their shielding/carrying cases to ensure that exposure to personnel does not increase.

If digital radiography is used as a diagnostics or information-gathering tool, no ASME code requirements need to be applied. Even in this case, however, ASME and ASTM procedures can be used as guidance when performing radiography measurements. In cases where the digital radiography examinations have to comply with code requirements, additional tests have to be done and a written procedure has to be prepared, which will include information for the achievable measurement parameters, such as unsharpness, latitude, contrast, spatial resolution and signal-to-noise ratio (SNR) of the radiographic image, as per ASME code requirements. As usual, image quality indicators (IQI) need to be used for assessing and standardizing the quality of the radiographic images.

2.6 Summary of the Performance Requirements

The NPP requirements for the applicability of digital radiography for valve inspection and monitoring can be summarized as follows:

- The new radiography system should offer reduced exposure time and reduced overall test time. This could lead to significant financial savings, and health and safety improvements due to minimizing dose to personnel.
- The expected range of valve sizes to be tested will be from 1/4” to 30”, which translates to a range in wall thickness from 0.1” to 8” (2 mm to 200 mm). Occasionally, even thicker valves will have to be tested, and in this case, an accelerator will have to be considered as a radiation source.

- The valves have to be tested in-situ, without being drained prior to the inspection.
- A detector with the best possible latitude, contrast and SNR, and with a reasonable spatial resolution, should be used. This is especially important for valves, where there is a very large range of thickness, and there is a need to observe internal parts with good image quality in order to allow for assessment of the state of the valve. Resolution requirements are not as important as in the case of weld inspection, so digital detectors are especially suitable for this task.
- The proposed detector should be capable of operating over the entire energy range from 100 keV to 15 MeV in order to ensure proper functioning with all possible radiation sources.
- For studying moving or vibrating internal valve parts, a real-time detector, such as a flat panel detector, should be considered.
- The radiographic equipment should be portable and easy to set-up and use. The detector should be able to fit in relatively congested areas. The system will preferably use radioisotope sources (as Ir-192 and Co-60), which are much easier to transport and position/orient for exposure than an x-ray tube. In addition, these sources are more easily certified for use in a station.

3. DETECTOR OPTIONS FOR DIGITAL RADIOGRAPHY

Industrial Radiography creates a two-dimensional projection of three-dimensional objects; thus it requires a position sensitive detector for x-rays and gamma-rays. Historically, the first position sensitive detector was photographic film. The advancement in digital detection of x-rays has made possible the use of different position sensitive detectors for radiography. The high interest in the digital electronic technologies for two-dimensional detection of x-rays and gamma rays was initially motivated by the obvious advantage of these techniques in the displaying, storage and communication of radiographic images.

The following digital radiography detectors are commercially available:

1. Computed Radiography (CR) Systems. The detector is based on photostimulable phosphor (PSP) flexible imaging plates. In many respects, this technique is similar to radiographic film. In the first step, the x-rays are absorbed in the phosphor material (usually $BaBrF:Eu^{+2}$) and a latent image is generated in the PSP. In the second step, the latent image is digitized by a read-out laser scanner. PSP can also be used with lead screens.

2. Flat Panel (FP) Pixel Detectors. These detectors consist of millions of small pixels, each pixel being a small radiation detector itself, and the signals from all pixels are read and put together to form an image. The following basic versions of FP detectors are available:

- <u>CCD-camera based detectors.</u> These detectors usually use fluorescent (scintillator) screens (such as barium lead sulfate, yttrium oxysulfide, lanthanum oxybromide, gadolinium oxysulfide Gd_2O_2S, etc.) to increase the absorption and to transform the x-rays to visible light, thus increasing the sensitivity of the overall detection of x-rays. Their main advantage is their low cost. Unfortunately, CCD sensors are very sensitive to radiation damage, so they have to be shielded. Also, CCD sensors are usually very small, so several of them have to be used in combination with either free-space lens optics or fiber-optic tapers. This makes CCD based radiographic detectors very bulky and not suitable for portable applications. The image transfer optics (lenses or fibers) also increase the cost and reduce the overall sensitivity of the detector. Another disadvantage is the relatively high thermal noise of CCD detectors. The electronics for these detectors are mostly 8-bit or 10-bit, which is not sufficient for NDE applications.

- *CMOS detectors.* These detectors also use scintillator screens to transform the x-rays to visible light. One can think of the CMOS detectors as computer random access memory (RAM) with a photodiode attached to each pixel, typically with a size of 25 to 50 μm. Nowadays, CMOS readout devices have noise levels comparable to CCDs, and the saturation capacity of a CMOS imager is usually several times larger than that of a CCD. CMOS detectors use the same fabrication processes and equipment that is used to make microprocessors, which decreases the production cost. Because the technology allows for very small linewidth, CMOS detectors have high resolution; typically pixel size is below 100 μm. CMOS technology also allows for integration of the imaging, timing and readout functions in one chip, further reducing production cost. The scintillator can be deposited directly over the pixels, making these detectors suitable for portable applications. CMOS detectors also have better power consumption than CCD detectors, which is also important for portable radiographic devices. Each pixel of a CMOS detector is wired separately. Unfortunately, CMOS detectors have limited real time capability.
- *Thin-film diodes matrix (TFD) and Thin-film transistors matrix (TFT).* There are two versions of these detectors: (i) direct detectors, which use a photoconductor (like α-Se, HgI_2, CdTe) to transfer the x-ray radiation to electrons; and (ii) indirect detectors, which use scintilators like CsI(Na), CsI(Tl), CsI(C), Gd_2O_2S(Tb) to transfer the x-ray radiation to visible light. Later TFD/TFT matrix detectors are also known as amorphous silicon (α-Si) flat-panel detectors. A significant advantage of amorphous silicon is the high radiation tolerance of these detectors. However, α-Si detectors have limited resolution (typically more than 100 μm pixel size) and relatively high noise. In addition, α-Si detectors are fabricated with a specialized dedicated manufacturing process, which increases the costs relative to the other technologies. Also, pixels are wired in series of columns and/or rows. Unlike CCD detectors, α-Si detectors do not require free-space optics or tapered fiber, because the scintillator layer is deposited directly over the pixels. These detectors usually have 14-bit electronics for signal digitalization.

The following performance parameters of radiographic detectors have to be considered when selecting a radiography system:

- ***Spatial Resolution***. Resolution describes the ability of a detection system to separate objects that are close together. It is usually expressed as *spatial frequency*, i.e., in terms of line-pairs per millimetre (lp/mm). The unaided human eye can distinguish about 8 to 10 lp/mm. For direct digital detectors, like α−Se, the resolution is determined by the pixel size, the pixel aperture, and the fill-factor. For indirect digital detectors, the resolution is determined not only by pixel size, but also by spreading of the light in the scintillator.
- ***Gray Scale Resolution***. The human eye can only see about 64 shades of gray, while an n-bit digital detector can generate an image with 2^n shades of gray and typical gray-scale resolution ranges from 8 to 16 bits.

- ***Sensitivity***. The sensitivity is defined as the radiation dose necessary to achieve a pre-determined detector signal, for example, the radiation dose in mR necessary to achieve an optical density of 2 or a digital signal in the middle of the signal range.
- ***Contrast (*or *Gradient)***. This characterizes the way in which the thickness differences in the radiographed object are transferred to detector signal differences. Generally speaking, the contrast for films is defined as the first derivative of the detector characteristic curve. Detector Contrast is (ΔSignal/ΔDose), while Object Contrast is (ΔSignal/ΔThickness). Object Contrast is usually measured in units of [counts/mm] or percent signal change for 1% thickness change.
- ***Latitude (Dynamic Range)***. This is defined as the exposure range (or the corresponding material thickness) for which the contrast (or signal-to-noise ratio for digital detectors) is bigger than a pre-defined value.
- ***Signal-to-Noise Ratio (SNR).*** For digital detectors, the SNR is defined as the ratio of the signal to the noise over a large area for uniform exposure of an object with fixed thickness.
- ***Contrast-to-Noise Ratio (CNR).*** CNR is defined as the ratio of the object contrast to the noise (usually measured as the standard deviation of the signal over a small uniform area). This is a very useful parameter, which can be used to quantify the visibility of defects in the object.
- ***Modulation Transfer Function (MTF) or Contrast Transfer Function (CTF)***. MTF describes the ability to image sine-wave shapes. MTF is a measure of signal transfer over a range of spatial frequencies.
- ***Detective Quantum Efficiency (DQE)***. This is an integral measure of dose efficiency, contrast, resolution and signal-to-noise ratio. DQE measures signal-to-noise transfer through the system as a function of spatial frequency.
- ***Energy Range.*** This is the range of energies over which we have sufficiently high x-ray quantum detection efficiency.

It should be noted that the above parameters depend on the specific application geometry, on the radiographed object, and on the radiation source used. Because of that, the published parametric data in the literature are difficult to compare, and in some cases, one detector seems to be better than the other detectors, but for different applications the opposite is true.

The following three radiographic detection systems were selected to be compared in detail:

- Film (analog, direct single-step detector).
- CR with PSP (digital, indirect two-step detector).
- α-Si indirect flat panel detector (digital, indirect two-step detector).

A quantitative parametric comparison of the selected detection systems is presented in Table 2 [1-6]. As can be seen, a relatively wide range of values is presented for both the MTF and the DQE functions because of their strong application dependence.

Table 2
Parametric Comparison of Different Radiography Detectors

Parameter	Film	CR	α–Si
Type	direct	indirect	indirect
	analog	digital	digital
Field of View	Any, Flexible	Max 40x50cm, Flexible	Max 40x50cm, Fixed
Energy Range	Full with multiple films	Full (better at <300 KeV)	Full (better at <200 KeV)
Spatial Resolution [μm]	< 10	20-200	50-400
Spatial Resolution [lp/mm]	50	3 - 10	4 - 8
Minimal Pixel Size [μm]	N.A.	N.A.	50
Sensitivity (mR for density of 2)	low (200 - 2000 mR)	medium (20 – 500 mR)	high (<0.1 - 2 mR)
Latitude (dynamic range)	1000 - 4000	64000 (16-bit)	16000 (14-bit)
Digitalization resolution	N.A.	12 to 16-bits	12 to 16-bits
Contrast	<1%	<1%	<1%
Signal-to-Noise Ratio	50-350	50-150	50-1000
Reusability	1	>1000	>100000
MTF [%] at 1 lp/mm	90 - 98	60 - 85	70 - 90
MTF [%] at 2 lp/mm	70 - 95	35 - 65	40 - 65
MTF [%] at 3 lp/mm	50 - 90	15 - 40	20 - 45
MTF [%] at 4 lp/mm	30 - 80	8 - 30	10 - 30
MTF [%] at 5 lp/mm	25 - 75	5 - 22	5 - 15
MTF [%] at 6 lp/mm	20 - 65	3 - 18	
MTF [%] at 8 lp/mm	15 - 55	2-12	
MTF [%] at 10 lp/mm	10 - 40	1-6	
DQE [%] at 0 lp/mm	25 - 30	10 - 40	15 - 55
DQE [%] at 1 lp/mm	20 - 25	5 - 32	10 - 50
DQE [%] at 2 lp/mm	15 - 20	4 - 15	8 - 30
DQE [%] at 3 lp/mm	10 - 15	3 - 8	5 - 15
DQE [%] at 4 lp/mm	8 - 12	2 - 5	3 - 8
DQE [%] at 5 lp/mm		1 - 2	

The main advantages common to all types of digital radiography systems can be summarized as:

- Improved latitude, i.e., a wider range of material thickness can be radiographed simultaneously.
- Improved productivity due to significantly reduced exposure times.
- Improved safety due to lower exposure levels.
- Improved environmental protection due to removal of chemical processing and hazardous chemicals.
- Improved information flow and data management due to integration and automation of the data collection, storage, archiving and transmission processes.
- Improved interpretation due to digital image processing.
- Reduced costs of consumables.

A qualitative comparison of main advantages and disadvantages of the classical and digital radiography systems is presented in Table 3 [6-12].

Table 3
Advantages and Disadvantages of Different Radiographic Detection Systems

Detector	Advantages	Disadvantages
Film	▪ Much experience and expertise. ▪ Much existing equipment. ▪ Trained personnel available. ▪ Covered by all regulations. ▪ Superior spatial resolution. ▪ Superior DQE. ▪ Dust and waterproof packed. ▪ Flexible and break-proof material. ▪ Storage period is > 50 years.	▪ Nonlinear sensitivity to x-ray intensity. ▪ Low sensitivity (high exposure dose). ▪ Limited dynamic range (latitude). ▪ Long processing time. ▪ Requires darkroom and chem. Processing. ▪ Requires a great deal of storage space. ▪ Not easy to communicate images. ▪ Uses hazardous chemicals. ▪ Sensitivity changes with temperature, etc. ▪ Single-use detector (high recurring cost).
Computed Radiography (CR) with PSP	▪ Can be used anywhere a film can be used. ▪ Flexible and break-proof material. ▪ High linearity. ▪ High dynamic range (latitude). Up to 100 times more than film. ▪ High sensitivity (lower exposure time, smaller exclusion zone, longer usability of isotopes). ▪ Reusable (>1000 cycles). ▪ No darkroom / chemical processing. ▪ Better environment safety. ▪ Digital storage, archiving, sharing. ▪ Digital image processing. ▪ Very good for field applications.	▪ Lower resolution than film or film/screen. ▪ Lower Resolution then $\alpha-$Se. ▪ High sensitivity in the low energy range (sensitive to scattered radiation). ▪ Low DQE. ▪ Two-step process, slower in comparison to Flat Panels detectors. ▪ Image lag (signal transfer from previous image). ▪ Sensitive to environmental changes. ▪ Requires periodic cleaning of PSP.
α-Si Flat Panels Detectors	▪ High sensitivity (lower exposure time, smaller exclusion zone, longer usability of isotopes). ▪ Wide latitude. ▪ Capable of high resolution real time radiography (faster than direct). ▪ High throughput. ▪ Automation/highly integrated.	▪ Flaws caused by dead pixel elements. ▪ Variations in background levels. ▪ Low resolution (pixel sizes smaller than 100µm do not offer improvements in resolution due to light spread in the scintillator). ▪ Poor quantum efficiency with thin scintillators. ▪ Sensitive to visible light. ▪ Higher initial/replacement cost.

The main limitations of digital radiography are:

- Lower spatial resolution in comparison to film radiography.
- Acceptability problems of digital radiography results for some specific standard code requirements, i.e., slow implementation of standards for digital radiography.
- Higher initial investment cost.
- Lower field of view in some cases.
- Application-sensitive performance, i.e., technique has to be adjusted for each detector.

4. COMPUTER MODELING AND MEASUREMENT RESULTS

In order to illustrate the advantages of digital radiography over classical film radiography, both computer modeling and measurements of different penetrameters were performed at Chalk River Laboratory, using two different digital radiography systems.

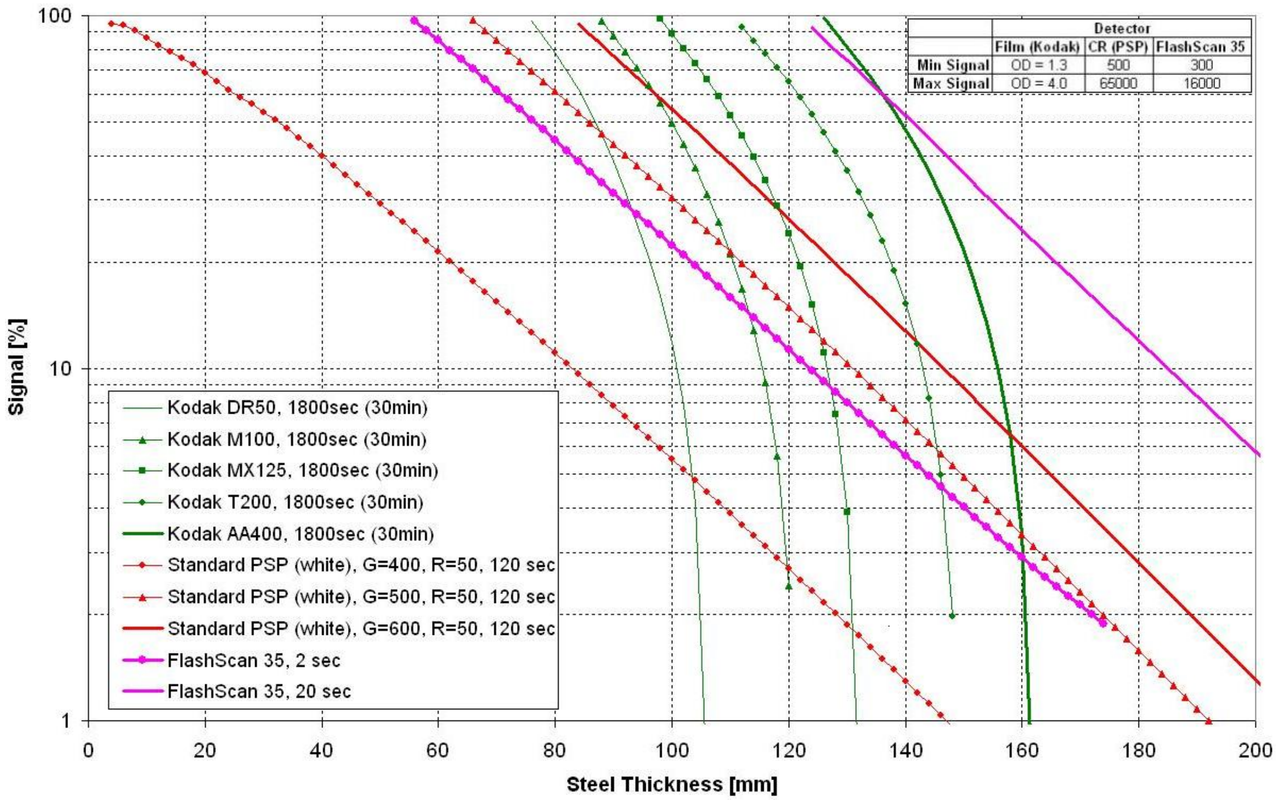

Figure 1 Calculated latitude (dynamic range) of different detectors for ^{60}Co (10 Ci).

Results from the computer modeling of the steel thickness range that can be radiographed with a single exposure to ^{60}Co (10 Ci), are shown for different detectors in Figure 1. For films (Kodak), the signal depends on the film speed and on the exposure time. For CR (PSP), the signal depends on the exposure time and on the gain and resolution of the laser scanner. For α-Si (FlashScan) flat panel detectors, the signal depends on the exposure time. Five Kodak films with different speeds were modeled, together with Fujifilm CR imaging plates (BAS-SR2040) in combination with a CIT DR-1400 scanner, and a FlashScan-35 flat panel detector. Single film can cover about 20-30 mm of thickness (all 5 films together can cover about 80 mm of thickness), while PSP and flat panel detectors can cover over 140 mm of thickness with a single exposure. In fact, our particular CR system allows for multiple scans of the PSP from a single exposure, which further increases the thickness range which can be radiographed simultaneously. As can be seen, digital detectors offer significantly better latitude in comparison to films. Also, the exposure time decreases from 30 minutes for films, to 2 minutes for PSP imaging plates, and to 2 seconds for the FlashScan-35 flat panel detector, which is a significant improvement in the required time for performing radiographic inspection.

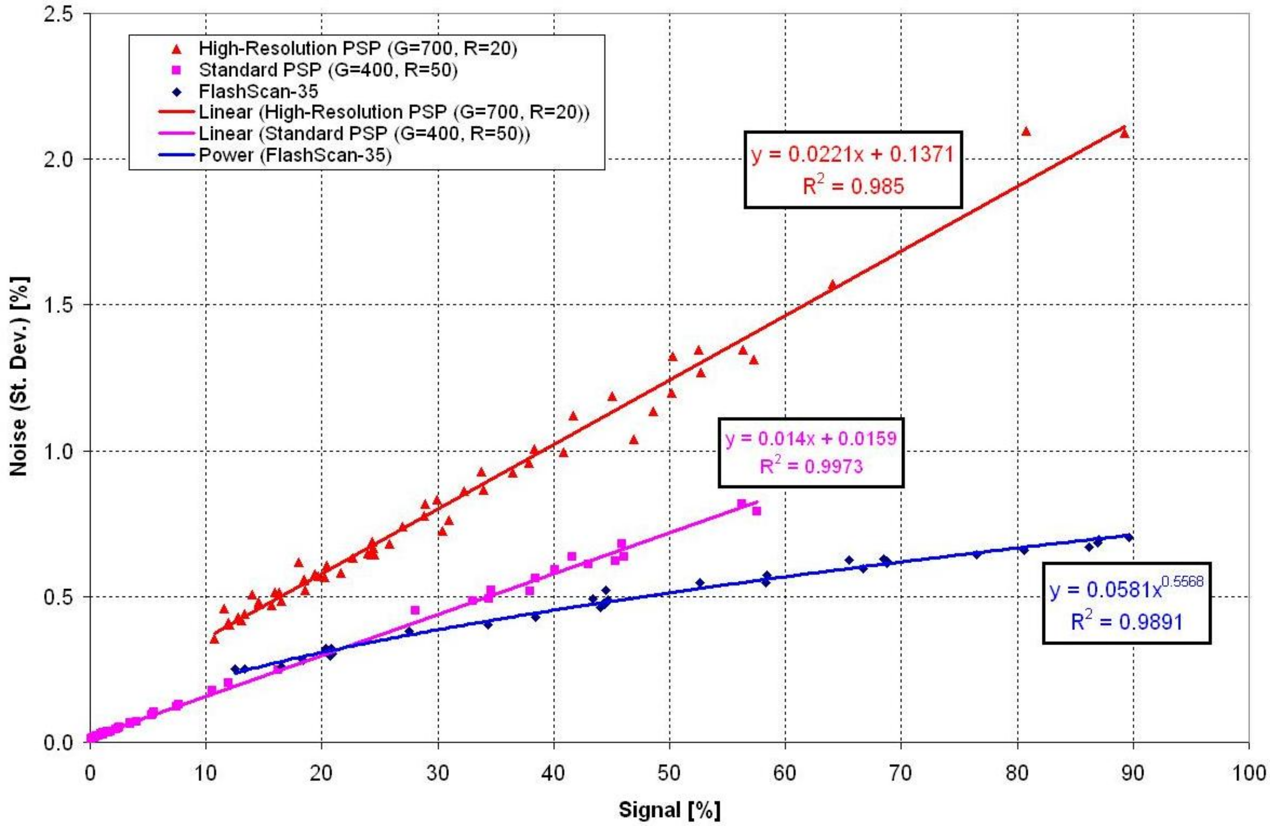

Figure 2 Measured noise characteristics of different digital detectors.

Measured noise characteristics of the digital detectors (Fujifilm standard resolution BAS-SR2040 and high-resolution BAS-MS2040, and Thales FlashScan-35 α-Si flat panel detector) are shown in Figure 2. As can be seen, PSP detectors have linear noise (i.e., the noise is linearly proportional to the signal level), while the flat panel detector has noise that is proportional to the square root of the signal level. The linear noise of the PSP detectors can be considered as one of the main disadvantages of the CR systems because it leads to saturation of the achievable signal-to-noise ratio (SNR), as can be seen in Figure 3. This limits the visibility of very small defects in thick objects for this radiographic technique. On the other hand, it should be noted that SNR is not a very important parameter when applying CR for valve diagnostics and monitoring, where relatively large thickness differences need to be observed. Flat panel detectors also offer the advantage of averaging multiple images, which further improves the SNR and CNR for these detectors.

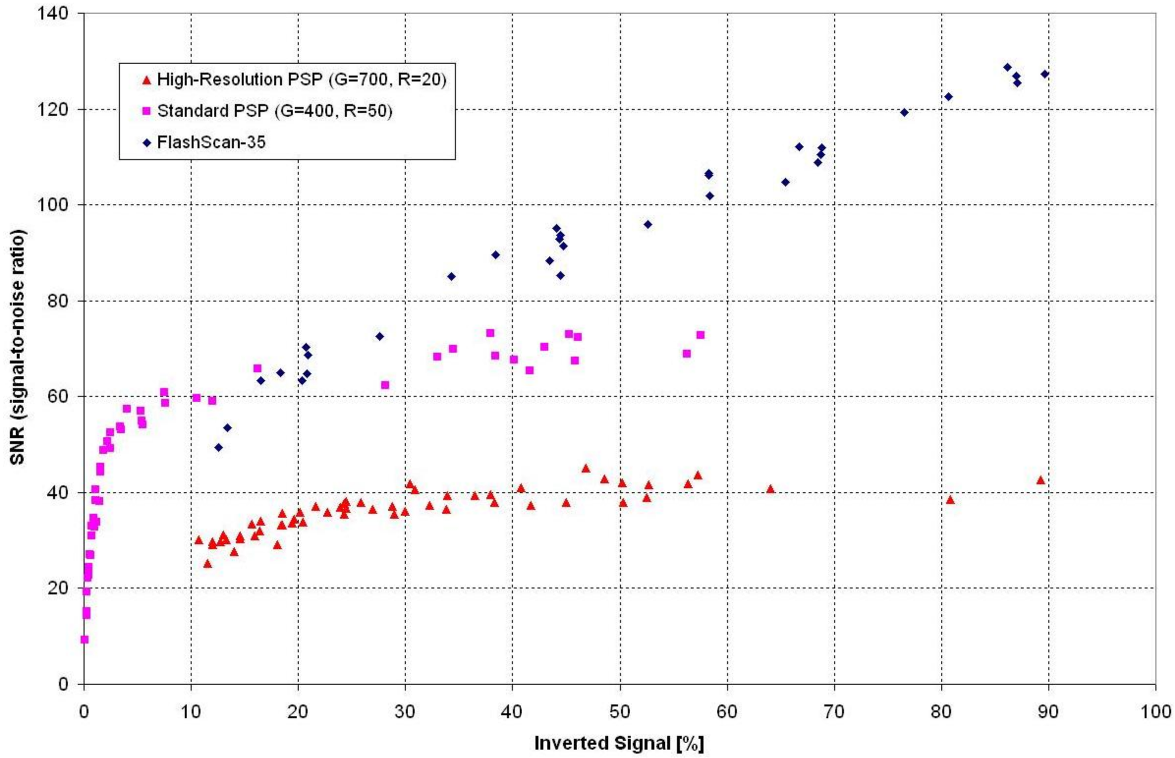

Figure 3 Measured Signal-to-Noise-Ratio (SNR) of different digital detectors.

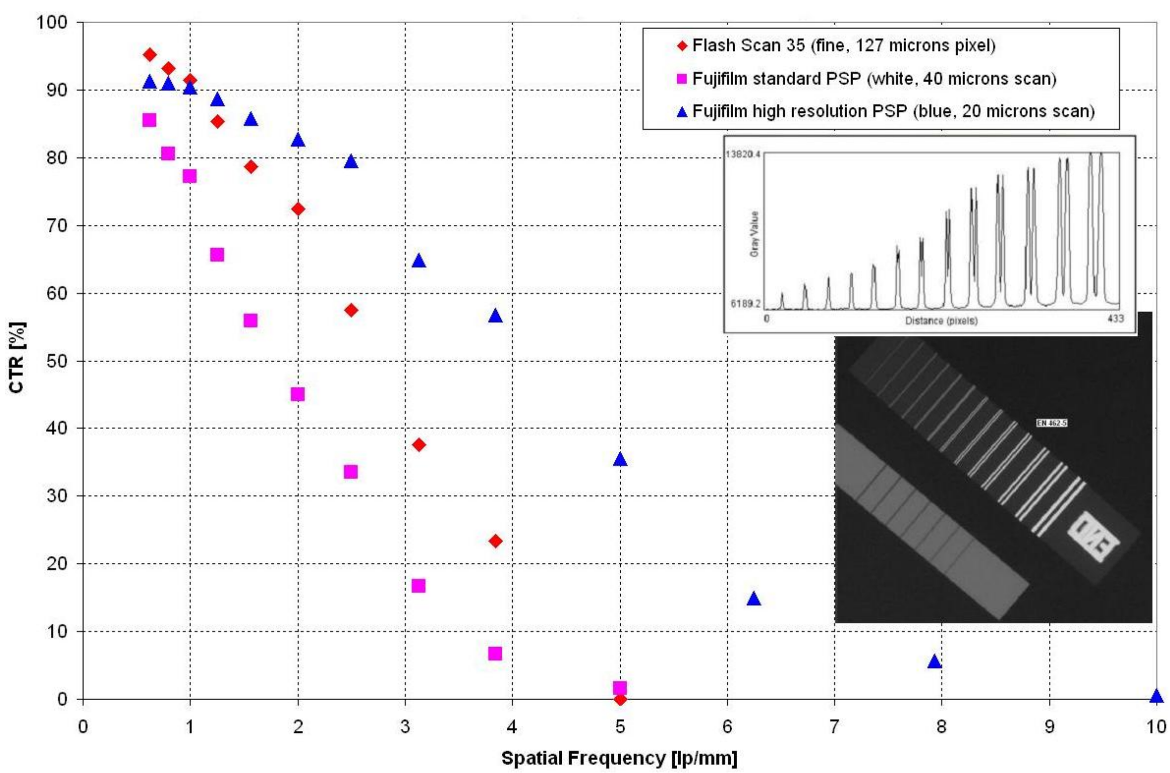

Figure 4 Measured Contrast-Transfer-Function (CTF, EN 462-5) of digital detectors.

Measured contrast-transfer-function (CTF) of different detectors is shown in Figure 4. As can be seen, the two tested digital detectors can separate details on the order of 150 µm (microns), i.e., the CTF is better than 20% for spatial frequency of 3 lp/mm.

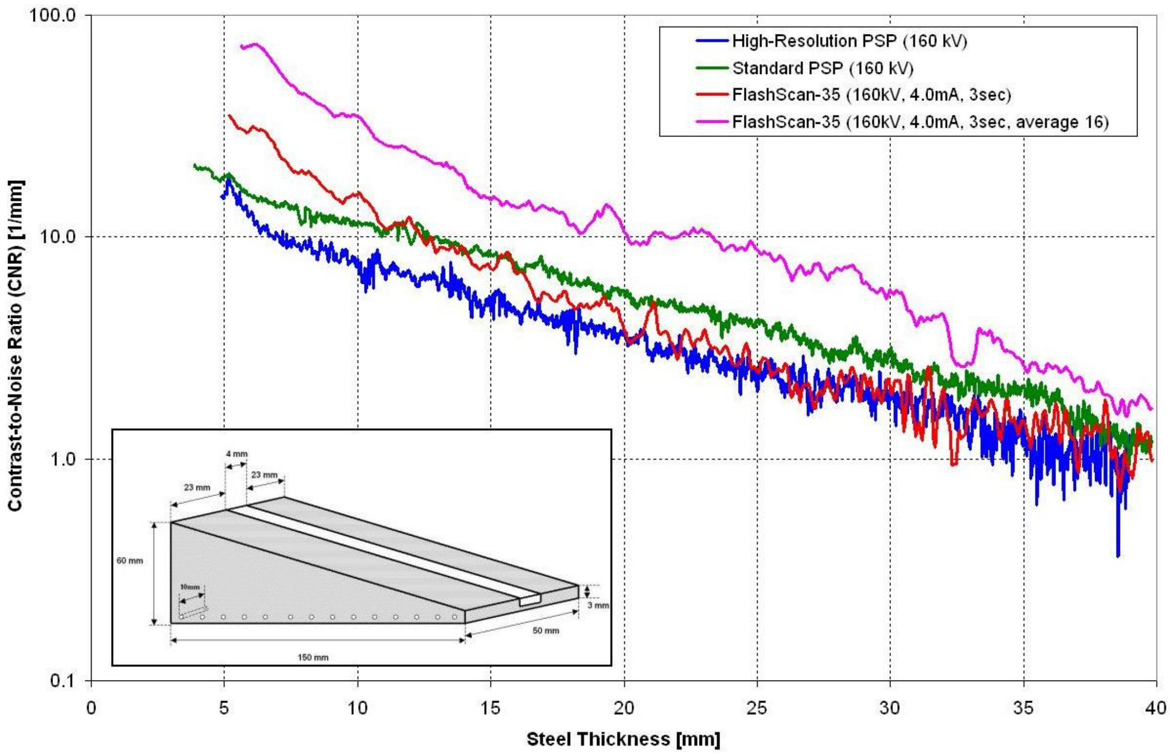

Figure 5 Measured Contrast-to-Noise-Ratio (CNR) of digital detectors.

Measured contrast-to-noise-ratio (CNR) of different detectors is shown in Figure 5. Measurements were done with a steel wedge with maximal thickness of 60 mm, using an x-ray tube (Tungsten anode, 160 kV). As per "ASTM Standard E94-00: Standard Guide for Radiographic Examination", the combination of an x-ray tube at 150 kV and radiographic film can be used for radiographing steel thickness from 9 mm to 36 mm (2.5 Half-Value-Layers (HVL) to 10 HVL), using multiple films or exposures. Digital detectors offer CNR better than 1:1 for the range zero to 40 mm with a single exposure.

Images of a ½ inch valve (max. steel thickness of 50 mm) taken with a CCD detector (8-bit), with a Fujifilm standard resolution PSP (BAS-SR2040, 16-bit DR-1400 scanner), and with a Thales FlashScan-35 (14-bit) flat panel detector, are shown in Figure 6. The images were taken with the X-ray tube at 150 kV voltage. As can be seen, the flat panel detector offers the best visibility of the internal parts of the valve.

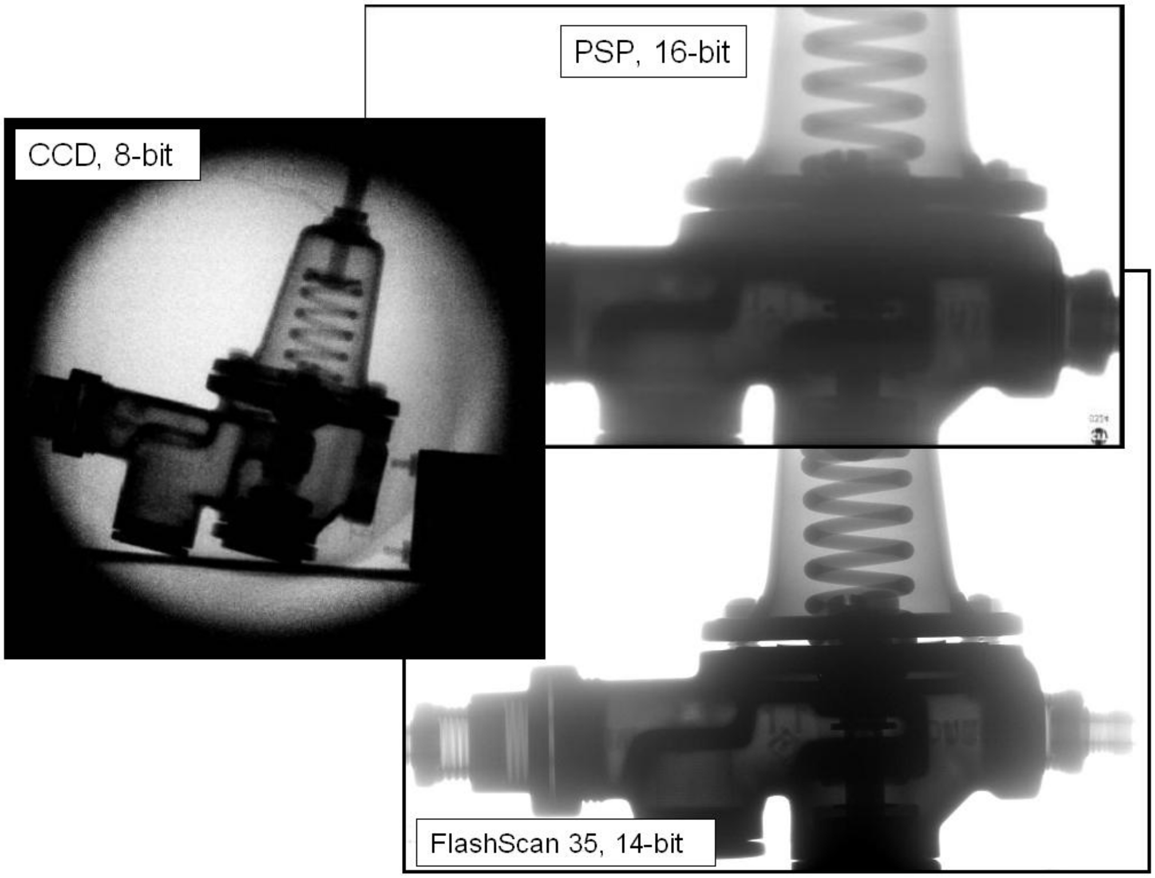

Figure 6 Images of ½ inch steel valve (max. thickness 50 mm) with different digital detectors.

5. CONCLUSION

Digital radiography is a very promising new technology that offers improved detection latitude (larger dynamic range) and better contrast, sensitivity, SNR and CNR than classical film radiography. This makes DR very suitable for valve inspection and monitoring, and in most cases DR should be the instrument of choice for this task. Another big advantage that DR can offer is the time and operational cost reduction, which translates into significant savings. Other benefits of DR systems are the elimination of chemical processing and disposal, and the associated health and environmental risks, the reduction of exposure rate to personnel, and the reduction of the necessary exclusion zone. The ability to apply digital image processing for image enhancement, and digital communication and storage of the test results, can lead to automation and improvement of the radiographic process.

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