DIGITAL X-RAY SOLUTION FOR STATE-OF-THE- ART RADIOSCOPIC TESTING OF WELD SEAMS OF WELDED STEEL PIPES ACCORDING TO DIN EN ISO 10893-7:2009-03

Andreas BEYER, Holger LUX, Michael WÜSTENBECKER
GE SENSING & INSPECTION TECHNOLOGIES GmbH, Ahrensburg, Germany

1 Introduction:

With the introduction of DIN EN ISO 10893-7:2009-03 there is now a new standard for the radioscopic inspection of weld seams of welded steel pipes. In this paper we discuss state-of-the-art weld-inspection solutions to meet this standard. We compare multiple industrial x-ray detectors in terms of their different performance factors and outline the critical system parameters for the successful choice of x-ray image chain- and system components for the entire inspection solution. We show that the correct choice of today's digital x-ray detectors not only helps to meet stringent standards but also drives improvements in inspection speed and throughput for automated inspection solutions to help prepare for the future.

2 Motivation

Weld inspection of helical- and longitudinal welded pipes according to DIN EN ISO 10893-7:2009-03 will soon become mandatory, as this standard follows recent advancements in digital x-ray detector technology.

On top of this, further customer-specific or international standards e.g. DNV, ASTM und API may apply. To be in compliance with these standards the inspection industry provides multiple solutions and combinations of components in the imaging chain (X-ray source, x-ray detector, handling systems and image enhancement and archiving).

Increasingly stringent requirements for pipe quality demand increasingly efficient inspection systems to ensure this high quality. By moving to more and more automated processes, modern x-ray inspection solutions need to combine high throughput requirements with the required inspection capability. Digital radioscopy systems provide this combination. Automated digital X-ray inspection supports an efficient production process and allows multiple possibilities for improvement because of fast and digital image acquisition, - enhancement, -analysis and long term archiving.

In this paper we discuss three typical and state- of- the-art digital x-ray detectors (DR) in terms of image quality and examine their application within automated x-ray inspection solutions in pipe mills.

3 Basic DIN EN ISO 10893-7:2009-03 requirements

This standard supports the recent developments in the field of digital radioscopy and defines the overall usage of this technology for storage plates/computed radiography (CR) or digital radiography (DR) using digital detector arrays.

Specifically, we look at fast DR radioscopic inspection solutions as a basis for high speed and automated weld inspection only.

3.1 Image Quality

The main image quality requirements of this standard with regard to spatial- and contrast resolution are defined IQIs as specified in ISO 19232-1 or ISO 19232-2 and ISO 19232-5 and ISO 17636. The following comparison is base on two different wire- and duplex wire IQIs (EN 462-1 and EN 462-5) defining spatial and contrast resolution requirements for different wall thicknesses.

Depending on the final usage of the welded steel pipe, ISO 10893-7 is divided into two image quality classes in terms of the spatial- and contrast resolution:

> **Class A** defines image quality requirements for radioscopic inspection using standard sensitivity for the majority of pipes in less critical applications.
>
> **Class B** defines image quality for an increased sensitivity and for a more stringent inspection e.g. for oil and gas transportation.

Furthermore a defined compensation principle applies:

> If both IQI sensitivities (here wire and duplex wire IQI) cannot be achieved by the used detector system, an increase in single wire visibility can compensate for un-sharpness values, which are too high. (i.e. if D11 and W14 is not achieved at the same time for a specific detector set-up, W14 and D8 provides an equal detection sensitivity).

Using this method, today's state of the art digital detector arrays (DDA) overcome the inherent limitations of larger pixel pitch compared with fine x-ray film and can now be used for weld inspection in compliance with ISO 10893-7.

Additional to these requirements, a third image quality metric is defined as the minimal signal-to-noise ratio (SNR_{norm}). SNR_{norm} is also broken down into two classes:

> **Class A**: $SNR_{norm} > 70$
>
> **Class B** $SNR_{norm} >100$

One of the key features of digital detector arrays compared with conventional industrial image intensifier technology is the possibility to increase the SNR by applying gain factors. To achieve the required image quality class the adjustment of the best SNR is explicitly mentioned with the ISO 10893-7.

3.2 Image processing

For digital x-ray image analysis systems some minimal functions and tools have to be provided in order to meet the standard:

- Digital image data shall be proportional to the x-ray dose rate
- Interactive image scaling to optimize the visible x-ray image quality
- Digital image filter functions, line/area-profile display and tools to optimize the SNR_{norm}
- Documentation of all image enhancement and -processing steps
- Classification of weld imperfections

- Image archiving of raw image data with full resolution (incl. offset and gain correction)
    - Redundant storage using adequate backup-strategies for min. 10 years
- Image display monitor requirements:
    - Min. luminous intensity 250 cd/m²
    - Min. 265 grey values to be displayed
    - Min.-max. light density ratio 1:250
    - Active area of min. 1000 x 1000 pixel with a pith < 0,25mm
    - The correct image display on a monitor has to be verified by a representative test image.

Today's digital x-ray image analysis programs e.g. GE's VISTAPLUS V in combination with long time storage software, like GE's Rhythm Archive, provides all the functions necessary to acquire, enhance, analyze and archive the inspection results. Furthermore automation of image quality verification and documentation ensures safe operation in compliance with the inspection requirements.

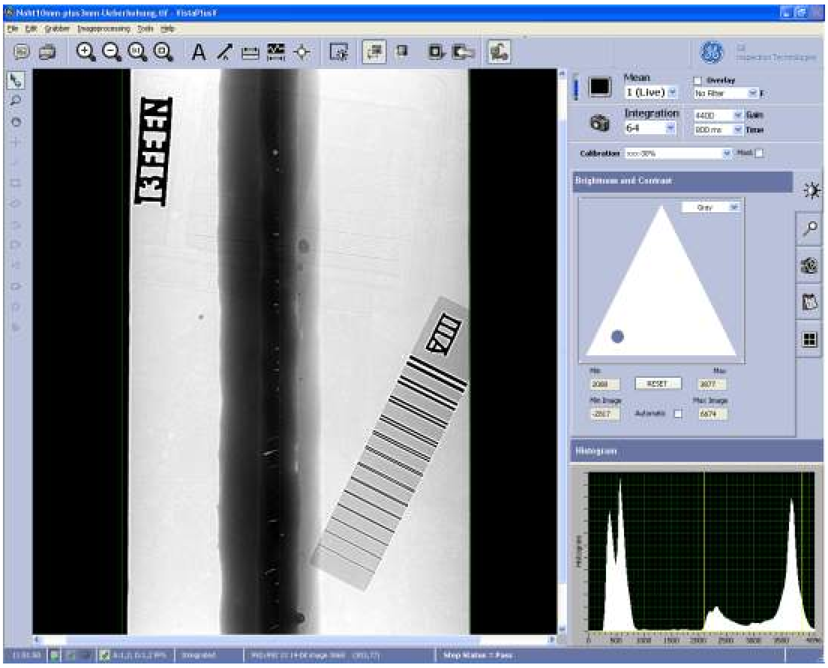

Figure 1: GE's VISTAPLUS V digital imaging software

4 Test set-up

For the comparison of suitable detectors we selected nine test samples of arc welded steel pipe sections with different thicknesses. The inspection was done by a certified NDT Master (Level III RT / DT) in the GE Sensing & Inspection Technologies x-ray laboratory.

The weld characteristics and dimensions are listed in table1:

Weld No.	Material	Basic material [mm]	Weld reinforcement [mm]
01	Fe	5,00	3,00
02	Fe	9,60	4,00
03	Fe	14,60	4,40
04	Fe	20,50	3,00
05	Fe	24,60	4,00
06	Fe	30,50	0,30
07	Fe	35,00	3,00
08	Fe	40,50	0,30
09	Fe	51,00	4,50

Table 1 : Weld samples

The test was set up in compliance with the specified procedure ISO 10893-7 section 6:

- The central beam shall be centered to the inspection section and perpendicular to the surface.
- Dependent on the image quality class, a deviation of image quality from the center to the edge of the inspection section shall not be larger than 10% (class B) or 20% (Class A).
- Single wall inspection
- Minimal distance between detector and weld surface

The aim of this study is to show the optimized x-ray set-up for inspection throughput and image quality focused on DDA's. The focus-to-detector distance (FDD) was therefore set to 1000mm resulting in a magnification of 1.3 for all tests.

All tests were performed using an ISOVOLT Titan E bipolar X-ray generator with an ISOVOLT 450 M2 0.4-1.0 HP x-ray tube using the large focal spot.

For the digital image acquisition, -enhancement and -analysis we used GE's VISTAPLUS V imaging system incl. a 19" TFT monitor. Both are in compliance with the requirements for the digital imaging functionality stated above.

Figure 2: GE ISOVOLT Titan E X-ray set

4.1 X-ray detectors

For the comparison and further discussions we analyzed three state of the art x-ray detectors:

GE VISTALUX 9S3-HR 9" industrial image intensifier

Input field in normal mode:	215mm (viewable input screen area)	
Digital camera technology:		
	AD converter:	12bit
	Frame rate (min.):	30 fps
	Image integration:	33ms (min.)
	Pixel matrix:	1004 x 1004 pixel

Perkin Elmer XRD1620 AN		**XRD0820 AN**
16" digital detector array		8" digital detector array
Total area:	410 x 410 mm^2	205 x 205 mm^2
Pixel pitch :	200µm	200µm
Frame rate (min):	3,5fps	7,5fps @ 200µm
Image integration:	285,6ms	133ms @ 200µm
Pixel matrix	2048x2048	1024x1024
AD converter	16bit	16bit

Note:

Due to the unavailability of the 8" detector during our test, it is assumed that the panel behavior of a 8" detector XRD0820 AN is comparable to a 16" version. As the integration time of the 8" equivalent is 46% of the 16" panel we apply this factor to all following timing discussions.

GE DXR 250RT-E

8" digital detector array	
Total area:	205 x 205mm^2
Pixel pitch:	200µm
Frame rate (max):	30fps @200µm
Image integration:	33ms (min.)
Pixel matrix	1024x1024
ADC	14bit

All of the above detectors are evaluated in terms of image quality and inspection speed such that they are suitable for operation in an automated inspection system.

One factor affecting the overall throughput of an inspection system is the handling time, pipe loading/unloading and processing speed between individual positions. Another factor is the acquisition time per shot. The acquisition time is the factor of frame rate, integration time per frame and number of frames integrated per shot. With the focus on throughput, we use an integration of 64 images for all image acquisitions in this comparison.

5 Key Findings:

5.1 Image Intensifier

The GE VISTALUX 9S3-HR industrial image intensifier (I.I.) represents proven x-ray detector technology and has been used in the NDT field, including application in automated weld inspection, for decades.

The reason we included this x-ray detector was to discuss the key differences to DDA'S and show how the ISO 10893 influences the choice of x-ray detectors for fast weld inspection in the future.

The VISTALUX 9S3-HR industrial image intensifier meets the stringent EN 13068-3 Class B special- and contrast resolution when operated at higher electronic magnification (input field < 215mm) and geometrical magnifications (> 1.3). Higher magnifications result in a smaller field of view and directly influence the number of inspection positions, and therefore inspection speeds, for a given pipe.

Higher geometric magnification as well as the large housing dimensions of an industrial image intensifier has influenced system designers to move the x-ray tube within the pipe and locate the associated Image Intensifier (I.I.) outside the pipe. This strategy was fine with unipolar x-ray tubes up to 225kV to ensure that small pipe diameter can be inspected. By using bi-polar x-ray tubes (≥ 320kV) to inspect pipes with larger wall thickness, the system design is challenged to incorporate much larger x-ray tubes and a critical high voltage power supply for inspecting pipes as long as 18m – 24,5m.

When directly comparing the requirements of EN 13068-3 with those of ISO 10893-7, we see that the latter is less stringent in terms of required special- and contrast resolution, disregarding the required SNR. A comparison in regards to the set of weld samples is listed in Table 2:

Basic material [mm]	Target Class B **ISO 10983-7** EN 462-1	Target Class B **EN 13068** EN 462-1	Target Class B **ISO 10983-7** EN 462-5	Target Class B **EN 13068** EN 462-5
5,00	W16	W16	D12	D10
9,60	W14	W15	D11	D9
14,60	W13	W14	D10	D9
20,50	W12	W13	D10	D9
24,60	W12	W13	D10	D9
30,50	W11	W12	D10	D9
35,00	W10	W11	D10	D9
40,50	W9	W10	D10	D9
51,00	W9	W10	D9	D9

Table 2: ISO 10893-7 and EN 13068 compare

Following the defined test setup as described above, the imaging results show that the image intensifier is in accordance with the stringent image quality requirements of ISO 10893-7 class B for wire and duplex wire IQI's through the whole test set from 5,0mm to 51,0mm of weld.

The IQI's were resolved using no additional image enhancement except for the 5,0mm weld. Using a magnification of 1,3 with the 5,0mm weld the D8 IQI could be resolved without further image enhancement to meet class A requirements.

To comply with class B on the 5,0mm weld further digital image filtering was applied to achieve the D9 IQI and meet class B image quality.

To meet the tough imaging requirements above 15mm of steel, an extended sensitivity mode (Illumination) was used. This Illumination mode enables longer frame rates using the special digital camera of the VISTALUX 9S3-HR in combination with the GE's VISTAPLUS V imaging software. This feature significantly broadens the usage of image intensifiers for thicker welds to achieve reasonable exposure times between 2 seconds for the 5,0mm weld and 12,8 seconds for 50mm Fe weld.

All of the above however need does not consider the min. SNR required by ISO 108923-7.

Using the image intensifier technology the required SNR is too low to meet the minimal SNR_{norm} of >70 for Class A and >100 for Class B according to ISO 10893-7.

The image intensifier performance is therefore not sufficient when the weld inspection of steel tubes have to be according to ISO 10893-7.

Basic material [mm]	Weld [mm]	kV	mA	Illumination mode [ms]	Total Exposure Time [s]	Target Class B **ISO 1093-7** EN 462-1	Actual EN 462-1	Target Class B **ISO 1093-7** EN 462-5	Actual EN 462-5	SNR_{NORM}
5,00	3,00	85	13,00	33	2,11	W16	W16	D10	D9*	56
9,60	4,00	120	10,50	33	2,11	W14	W15	D9	D8	59
14,60	4,40	150	10,00	33	2,11	W13	W13	D9	D8	61
20,50	3,00	160	9,00	100	6,40	W12	W13	D9	D8	63
24,60	4,00	185	7,30	100	6,40	W12	W12	D9	D8	60
30,50	0,30	265	5,00	100	6,40	W11	W11	D9	D8	40
35,00	3,00	295	5,00	150	9,60	W10	W11	D9	D8	66
40,50	0,30	320	4,60	100	6,40	W9	W11	D9	D8	65
51,00	4,50	450	3,30	200	12,80	W9	W10	D9	D8	62

Table 3: Test results of the VISTALUX 9S3-HR Image Intensifier

* Including additional high pass filter.

5.2 Digital Detectors

Digital detector arrays (DDA) or flat panel detectors are increasingly used in the NDT field for various applications in Oil & Gas, Transportation, Energy and Aerospace.

Not only are the digital panels well suited for pipe weld inspection because of the compact size but also for the unique feature to increase the signal to noise level and therefore the image quality with higher gain factors.

For the evaluation of weld inspection, we compared two different digital detectors in terms of their imaging performance and suitability for this purpose.

The two digital detectors used were the PerkinElmer XRD1620AN (XRD0820AN) and the GE DXR 250RT-E. Again, for better comparison in terms of the throughput, we simulated the PerkinElmer 8" panel XRD0820 AN by taking only 46% of the XRD1620 frame rate for further discussions.

5.2.1 PerkinElmer XRD1620AN / XRD0820AN

The results of the image quality tests listed in Table 4 for the XRD1620AN/ XRD0820AN show that this panel technology accomplishes all IQI's and SNR_{norm} requirements to meet the ISO 10893-7 class B.

The wire- and special resolution IQI's were resolved using no additional image enhancement except for the 5,0mm weld. Using a magnification of 1,3 with the 5,0mm weld the D8 IQI could be resolved without further image enhancement to meet class A requirements. To comply with class B on the 5,0mm weld further digital image filtering was applied to achieve the D9 IQI.

Due to the compensation principle described before, an increase in single wire visibility (EN 462-1) can compensate too high un-sharpness values (EN 462-5) of the duplex wire IQI.

Base material [mm]	Weld [mm]	kV	mA	Total Exposure Time [s]	Target Class B **ISO 1093-7** EN 462-1	Actual EN 462-1	Target Class B **ISO 1093-7** EN 462-5	Actual EN 462-5	SNR_{NORM}	Max. DDA signal in % of total
5,00	3,00	100	15,00	7,86	W16	W19	D12	D9**	136	4%
9,60	4,00	170	8,00	7,86	W14	W17	D11	D8	122	8%
14,60	4,40	225	6,60	7,86	W13	W16	D10	D8	131	8%
20,50	3,00	242	6,10	14,72	W12	W15	D10	D8	134	6%
24,60	4,00	260	5,60	29,44	W12	W15	D10	D8	120	7%
30,50	0,30	320	4,60	29,44	W11	W15	D10	D8	148	7%
35,00	3,00	450	3,30	58,88	W10	W14	D10	D8	151	9%
40,50	0,30	450	3,30	58,88	W9	W14	D10	D8	166	8%
51,00	4,50	450	3,30	58,88	W9	W13	D9	D8	153	5%

Table 4: Test results XRD1620AN/ XRD0820AN*

* Exposure time values are according to 46% of the 16" panel to simulate the XRD 0820AN

** Including additional high pass filter.

The following significant aspects of the results are especially interesting:

1 A significant aspect of weld inspection is the fairly homogeneous wall thickness throughout the image and region of interest (ROI). Contrast resolution is not as critical as for other inspections like castings with complex structures of significantly different wall thicknesses within the ROI. The last column of Table 4 shows the mean grey value in the base material in regard to the total available. In average only 7% of the available dynamic range (of up to 16 bit (65536)) is used here.

2 The XRD 0820AN is a compact detector with small overall dimensions. This is specifically important when inspecting smaller tubes and pipes, with the advantage of operating the x-ray detector within the pipe. The detector housing measures 335mm x 320mm x 50mm (WxDxH). Depending on the mechanical set-up of the testing machine, the compact housing enables the inspection of pipes with an inner diameter of less than 450mm.

5.2.1 GE DXR 250RT-E

The test results in Table 5 show that the DXR 250RT-E also accomplishes all IQI's and SNR_{norm} requirements to meet the ISO 10893-7 class B. The IQI's were resolved using no additional image enhancement except for the 5,0 mm weld. Using a magnification of 1,3 with the 5,0mm weld the D8 IQI could be resolved without further image enhancement to meet class A requirements.

To comply with class B on the 5,0 mm weld further digital image filtering was applied to achieve the D9 IQI image quality.

Base material [mm]	Weld [mm]	kV	mA	Total Exposure Time [s]	Target Class B **ISO 1093-7** EN 462-1	Actual EN 462-1	Target Class B **ISO 1093-7** EN 462-5	Actual EN 462-5	SNR_{NORM}	Max. DDA signal in % of total
5,00	3,00	100	18,00	2,11	W16	W19	D12	D9*	143	9%
9,60	4,00	172	9,80	2,11	W14	W17	D11	D8	166	17%
14,60	4,40	225	8,00	6,40	W13	W16	D10	D8	211	26%
20,50	3,00	238	6,10	9,60	W12	W15	D10	D8	148	17%
24,60	4,00	250	5,00	11,52	W12	W15	D10	D8	134	28%
30,50	0,30	310	4,60	25,60	W11	W15	D10	D8	191	16%
35,00	3,00	360	4,00	32,00	W10	W14	D10	D8	141	12%
40,50	0,30	385	3,80	38,40	W9	W14	D10	D8	172	15%
51,00	4,50	450	3,30	64,00	W9	W13	D9	D8	151	11%

Table 5: Test results DXR250RT-E

* Including high pass filter.

The following significant aspects of the results are especially interesting.

1 Figure 3 shows the total exposure times of the DXR 250RT-E to meet the imaging requirements compared with the other detectors. Due to the fast frame rate of 30fps of this panel technology, the total exposure time is much faster than the XRD0820AN panel. Especially at thinner base material at or below 9,6mm, the panel is as fast as the I.I. in real time mode. The image intensifier, however can not be considered as benchmark as it does not comply with the required SNR_{norm}.

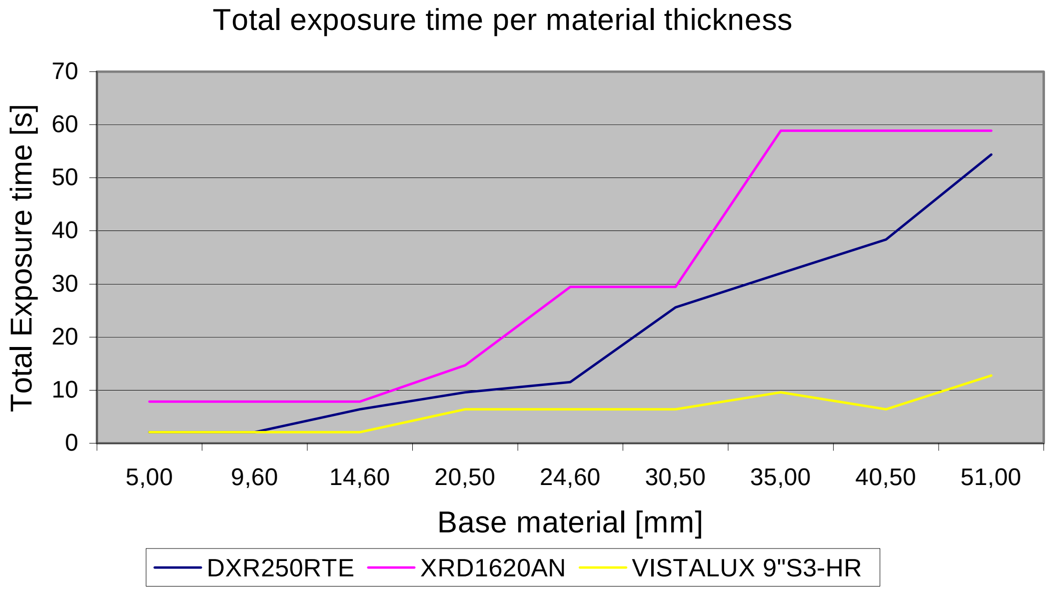

Figure 3: Exposure time per position to meet special- and contrast resolution of ISO 10893-7

2 The DXR detector provides a 14bit ADC for high contrast resolution. With the available 14 bit this panel is well suited for weld inspection with mean grey values in the base material between 9% and 28% of the total available range. In the max. grey value in % of the total range is plotted for all three detectors.

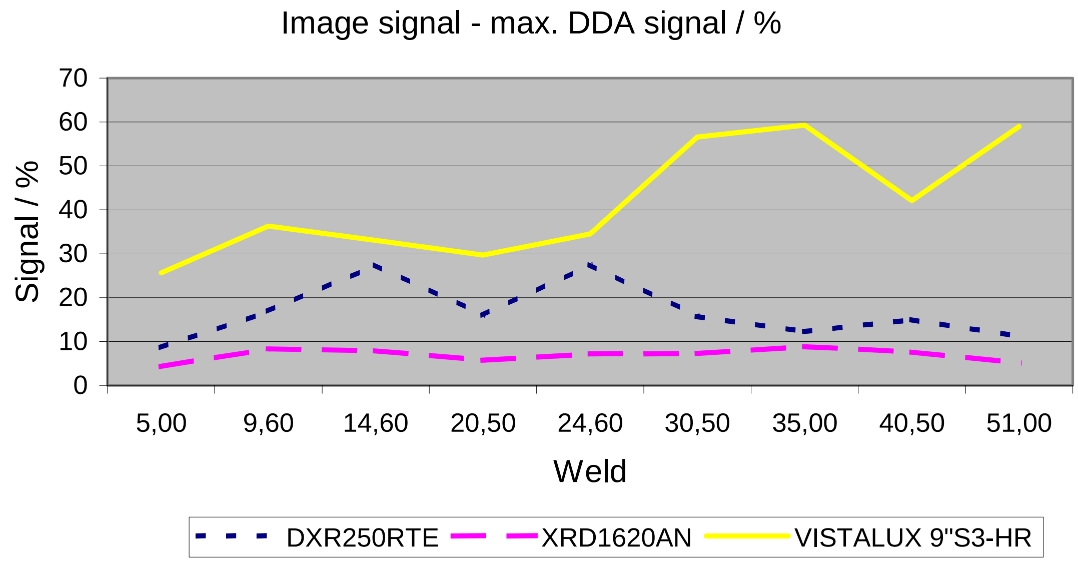

Figure 4: Max. dynamic range in % of total available

3 The DXR 250 RT-E is a very compact detector with small overall dimensions. This is specifically important when inspecting smaller tubes and pipes, with the advantage of operating the x-ray detector within the pipe. The DXR 250RT-E panel measures 260mm x 260mm x 114,3mm (WxDxH) and is therefore even more compact and suitable for pipe-inspection than the XRD0820AN with 335mm x 320mm x 50mm (WxDxH). The DXR 250RT-E therefore offers more potential to inspect smaller diameter pipes (≥ 360mm) due to the compact housing.

4 Looking at the necessary energy to meet the IQI requirements for different base material thicknesses shows that the DXR 250RT-E is more sensitive in the range of thicker base material than the XRD 1620AN panel. Therefore using a DXR 250RT-E technology needs less high voltage (kV) for testing thicker pipes. With the higher sensitivity compared to other panels further cost savings can be achieved by using smaller x-ray source equipment as well as necessary x-ray shielding.

Energy distribution

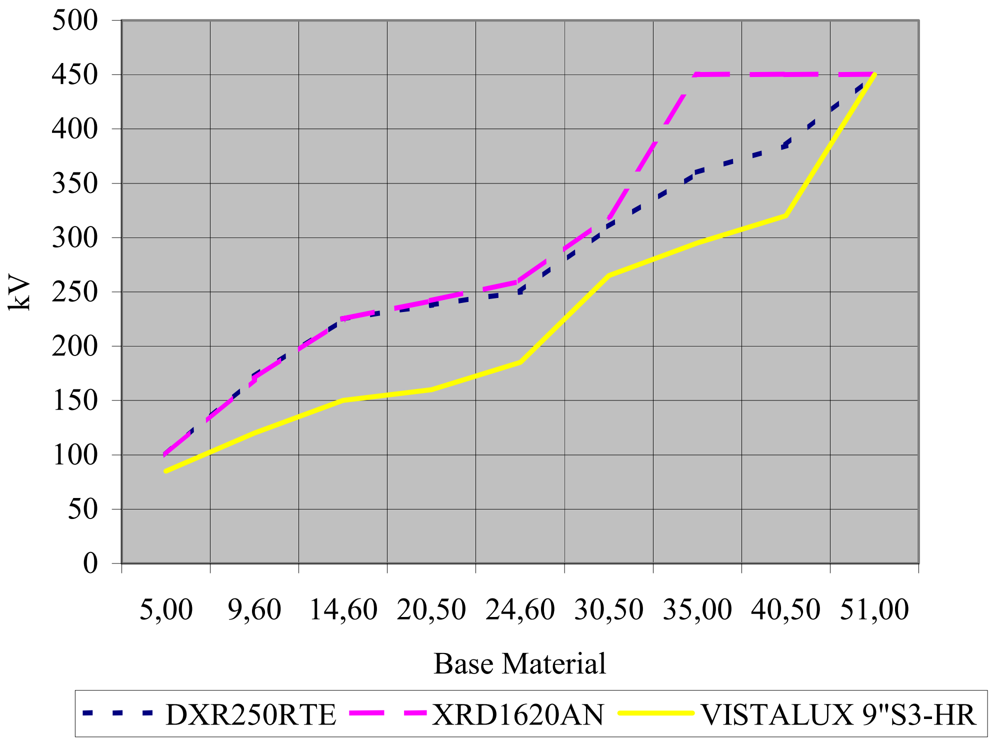

Figure 5: Energy requirements to meet special- and contrast resolution of ISO 10893-7

6 Inspection System Solution

Many pipe mills are using turnkey x-ray inspection systems for longitudinal-, spiral welds or weld end inspection to verify any indication of the mandatory and mostly automated UT inspection in accordance with standards like API 5L, ISO 12096 and DNV-OS-F101. Automated x-ray inspection systems are also used for 100% weld inspection as defined with end customers and to ensure the highest pipe quality.

Typical pipe inspection systems use a long iron boom to support either x-ray tube or detector from the inner side of the tube. A synchronized manipulation system on the outside of the pipe supports the corresponding x-ray detector or x-ray tube to ensure the correct x-ray set-up.

The necessary x-ray protection is built, brick-b-brick around the inspection system.

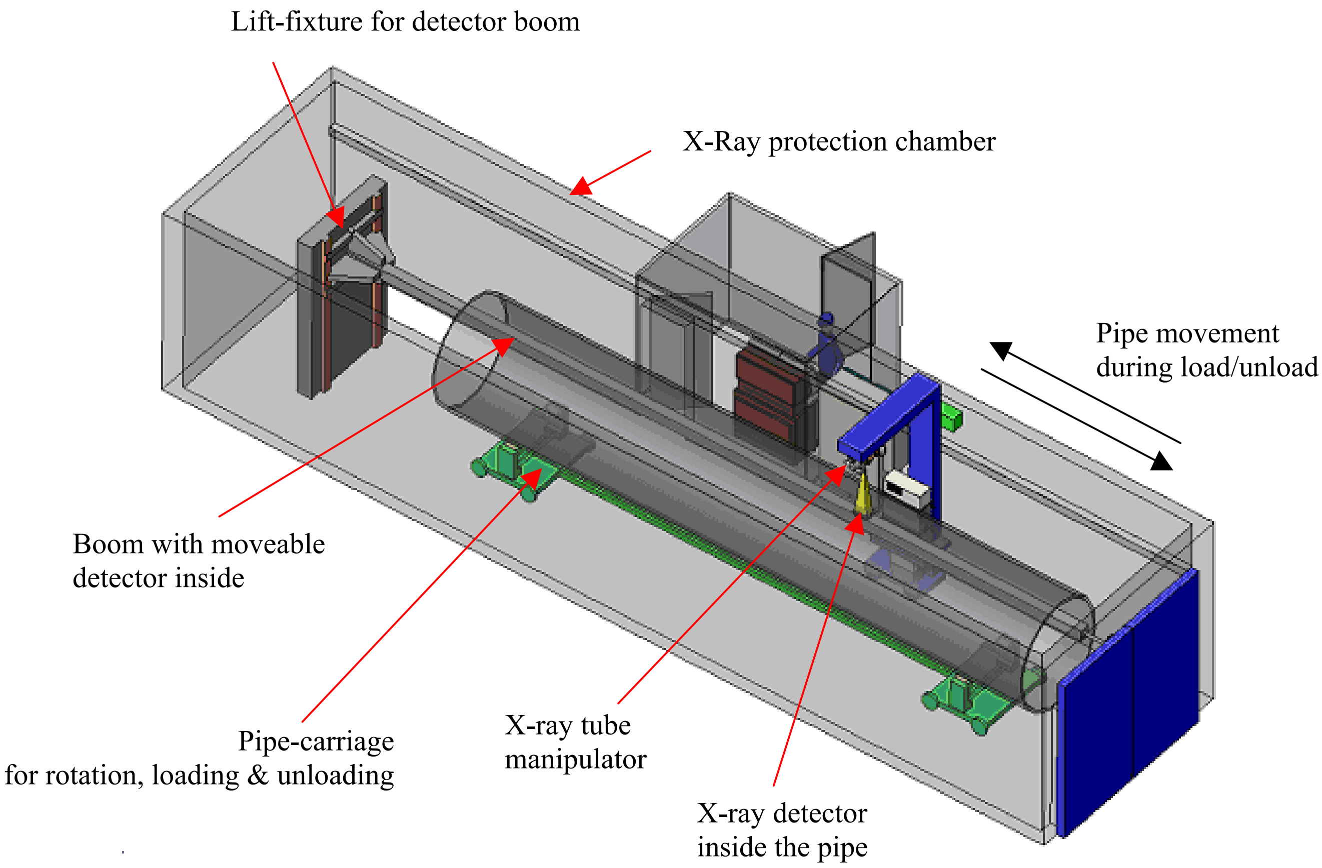

Figure 6: GE Pipe Inspection System

In process inspection, systems are also defined by the throughput capability. With x-ray inspection systems various aspects of the workflow contribute to the overall cycle time.

The total inspection speed / throughput T of an automated pipe inspection system equates to:

$$T = L + U + \sum_{1}^{n} (t_n * I_{\text{int},n}) + (n-1) * M$$

With:

- T: Total inspection time per pipe
- L: Time for pipe loading & pipe identification (e.g. 250sec.)
- U: Time to unload the pipe after inspection(e.g. 250sec.)
- n: Number of total inspection positions to cover necessary pipe length (e.g.85 for a 12,5m pipe)
- t_n: Acquisition time per frame [ms] at inspection position n (e.g. 33ms)
- $I_{\text{int, n}}$: Number if integrated frames at inspection position n (e.g. 64)
- M: Time to physically move from one inspection position to the following (e.g.1s)

In Figure 7 we see the typical overall cycle time for a 100% inspection of 12,5m SAW pipes considering two different detectors at wall thicknesses from 5,0mm to 51mm:

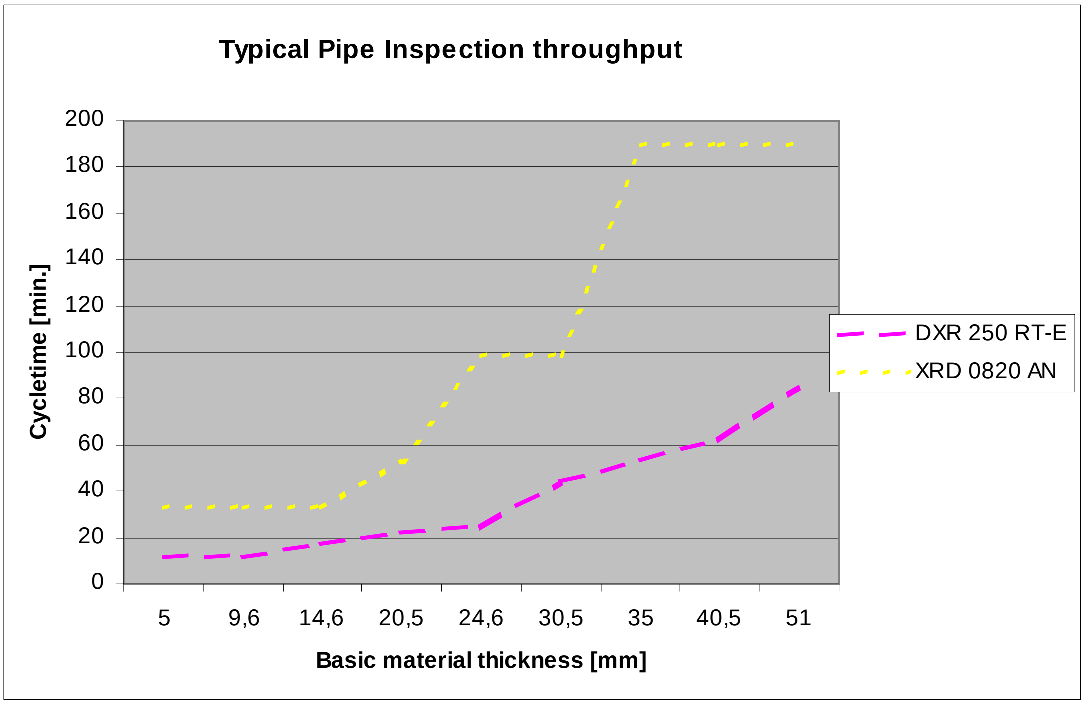

Figure 7: Typical testing machine throughput for a 12,5m SAW pipe

One of the most significant driving factors of inspection throughput is the acquisition time per position as this time adds to every single position during the inspection. For a 12.5m pipe at least 85 positions are needed, including a safety overlap.

By using a DXR 250RT-E detector with its unique frame rate we can see that the throughput is up to four times faster than with other panels.

The test results in Figure 7 show that the benefit of the faster and more efficient detector also increases with higher wall thickness.

A state-of-the-art pipe inspection system like the pipe inspection system from GE Sensing & Inspection Technologies utilizes the same key imaging chain modules as discussed above including the DXR 250RT-E detector, ISOVOLT Titan E x-ray generator and an appropriate x-ray tube for the expected pipe thickness. The digital image processing software VISTAPLUS V completes this turnkey solution.

With a recently designed new boom technology the pipe inspection system provides now much higher payload (for x-ray detectors) at smaller boom diameter. With this technology the system is able to move the compact DXR 250RT-E detector panel inside a 24,5m long pipe with an inner diameter as small as 360mm. Much smaller pipes can now be tested digitally in a single wall inspection mode.

Figure 8: Pipe inspection with DXR 250RT-E

7 Conclusion

Automated pipe weld inspection is driven more and more by stringent economic aspects throughout the entire production process. X-Ray inspection is an integral part of this process. Automated inspection systems not only have to comply with international standards like the ISO 10893-7 and others but also have to have a high throughput.

This paper compared three state-of-the-art x-ray detectors in terms of their imaging performance and operation for automated pipe weld inspection from 5,0mm – 51mm Fe welds.

Even though the image intensifier Vistalux 9” S3 HR with 1k x 1k digital camera and 12bit contrast resolution is in compliance with the spatial- and contrast resolution requirements according to ISO 13068-3 class B, the image intensifier-based detector does not meet the newly established ISO 10893-7 class B in terms of the required normalized signal to noise ration (SNR_{norm}).

The digital detector arrays XDR1620/0820 and DXR 250RT-E on the other hand show very good performance and meet all imaging requirements according to ISO 10893-7 image quality class B.

However considering the entire pipe inspection system solution, it is important to consider the physical aspects of the panel, the achievable inspection speed as well as the sensitivity to meet the imaging standards at lower energy levels.

The comparison has shown that the panels offer different performances in terms of image acquisition time, sensitivity and size. The DXR 250RT-E improves throughput with higher sensitivity in a small panel housing.

In combination with the pipe inspection system, including its advanced boom technology, this results in a powerful solution for a wide application range of pipe, enabling single wall inspection of very small pipe diameter down to 360mm and ensuring up to four times faster inspection than other system solutions.

8 References

[1] ISO 10893-7 Non destructive testing of steel tubes- Part 7: Digital radiographic testing of the weld seam of welded steel tubes for the detection of imperfections

[2] ISO 19232-1:2004 (E) Non-destructive testing – Image quality of radiographs – Part1: Image quality indicators (wire type)-Determination of image quality value

[3] DIN EN 13068-3 Radioscopic testing - Part 3 : General principles for the radioscopic testing of metallic materials by x- and gamma rays.