The HOIS recommended practice for in-service computed radiography of pipes

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Abstract
The comparatively new technology of computed radiography (CR) for NDT imaging has a number of advantages over traditional film-based radiography including reduced exposure times, and greater dynamic range. In addition, it does not require facilities for the development of radiographic film, which can be difficult to install and maintain, given the often restricted deck facilities space in an offshore environment. However the technology associated with CR is substantially more complex than film, and, in the absence of any internationally recognised standards for in-service radiographic inspection, the quality of the resulting CR images can be variable.

To improve the quality control of this form of inspection, the HOIS JIP has developed a recommended practice (RP) covering CR for the in-service inspection of pipes for wall loss type flaws (corrosion, erosion). This project involved a series of experimental trials to first develop and then validate the recommendations, and also to quantitatively compare the characteristics of different commercially available CR systems. Draft EN Standards based on this work will shortly be issued for public comment.

The results of the CR trials undertaken during this project and the main recommendations of the recommended practice are described. The full RP can be downloaded from http://www.hoispublications.com

Keywords: Computed radiography, pipes, in-service inspection, recommended practice

1. Introduction

Computed Radiography (CR) is a comparatively new technology [1], [2] in which radiographic film is replaced by a flexible, re-usable imaging plate (IP), that incorporates a thin layer of a photostimulable storage phosphor. A latent image is created when the IP is exposed to ionising radiation. This image is then readout using a laser scanner to give a digital radiograph which is displayed and analysed on a computer. CR has a number of advantages over traditional film-based radiography for NDT. These can include reduced exposure times, and greater dynamic range. In addition, CR does not require facilities for the development of radiographic film, which can be difficult to install and maintain, given the often restricted deck facilities space in an offshore environment.

For these reasons, CR is being used increasingly for in-service inspection of pipes within the oil and gas industry, where the flaws of concern are generally wall loss in the form of corrosion and/or erosion. The most widespread application is the combination of the tangential and double wall double image techniques to the inspection of small diameter pipes having 2" to 3" (50mm to 75mm) diameter.

However the technology associated with CR is substantially more complex than film, and, in the absence of any internationally recognised standards for in-service radiographic inspection, the quality of the arising CR images can be variable. Following disappointing results from an
early blind trial of CR on corrosion flaws in pipes, the HOIS JIP [3] initiated a project to develop a recommended practice (RP) covering CR for the in-service inspection of pipes for wall loss type flaws. The aim of this RP is to provide guidance aimed at improving the control of the quality of this form of inspection.

In drawing up this recommended practice, a series of experimental CR trials were undertaken to first develop and then validate the recommendations, and also to compare quantitatively the characteristics of different commercially available CR systems. An initial version of the HOIS Recommended Practice for the in-service inspection of wall loss in pipes by computed radiography has now been published [4], [5] and is freely available as a web download. This paper gives a summary of the main topics covered by that document, and describes the improved results obtained in a follow-up blind trial undertaken in accordance with the RP.

2. **Scope of the CR recommended practice**

The HOIS CR recommended practice covers the in-service inspection of pipes for wall loss type flaws (e.g. corrosion pitting, generalised corrosion and erosion) using computed radiography (CR). The pipes may be insulated or not, and can be assessed where loss of material due, for example, to corrosion or erosion is suspected either internally or externally.

The following inspection techniques are covered:

1. Double-wall single image (DWSI) radiography for the inspection of discrete wall loss flaws by their effects on image grey level.

2. Double-wall double-image (DWDI) radiography for the inspection of discrete wall loss flaws by their effects on image grey level.

3. Tangential inspection techniques for detection and through-wall sizing of wall loss, including (a) with the source on the pipe centre-line, and (b) offset from it by the pipe radius.

Note that DWDI is often combined with tangential radiography with the source on the pipe centre-line. This is sometimes referred to as profile radiography, but this term is not used here.

Two different qualities of radiography are considered:

A *standard quality* of computed radiography for wall loss inspection. This has less demanding quality requirements than those defined for weld inspection, in EN 1435 [6] for example, since, in general, wall loss flaws are easier to detect than typical welding flaws. For tangential radiography, standard quality is sufficient when the wall loss is approximately uniform, not isolated pitting.

A *higher quality* of computed radiography for wall loss inspection has also been considered. This is for CR inspections requiring higher quality (e.g. inspection of small pitting flaws). For tangential radiography, higher quality is recommended when there is a requirement to size pitting flaws.
3. Main sections of the HOIS CR recommended practice

The main sections of the HOIS CR recommended practice include:

- Selection and types of radiation sources
- Recommended source to detector distances (SDD) for DWSI, DWDI and tangential inspection
- CR image quality criteria, including normalised signal-to-noise ratio (SNR_N) and target single-wire IQI values
- Guidance on exposure times
- Circumferential and axial coverage
- Penetrated thickness measurements (computer analysis of CR image grey levels to estimate through-wall extent of wall loss)
- Tangential radiography, including source positioning, dimensional calibration, measurement techniques, cursors and grey-scale profiles
- Image processing and handling

For further details on all the above topics, the reader is referred to the full RP [4]. However, further details of some of the key recommendations are given below.

4. Key recommendations

4.1 Source selection

The HOIS CR RP focuses on the selection of isotope sources (Ir 192, Se 75 and Co60) as these are overwhelmingly the most common radiation sources used for in-service inspection. For the double wall techniques, the recommendations for pipe wall thickness generally follow those of EN 1435 for weld radiography.

For the tangential technique applied to a pipe with wall thickness WT and outside diameter OD, the maximum penetrated thickness, \( W_{\text{max}} \), through the pipe wall occurs for a line forming a tangent with the inner diameter. For \( WT < OD/2 \), \( W_{\text{max}} \) is given by

\[
W_{\text{max}} = 2 \sqrt{WT(OD - WT)} \tag{1}
\]

Source selection is then based on the following approximate maximum tangential paths for the different sources:

<table>
<thead>
<tr>
<th>Isotope source</th>
<th>Approximate maximum tangential path (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Standard quality</td>
</tr>
<tr>
<td></td>
<td>(for generalised wall loss)</td>
</tr>
<tr>
<td>Se 75</td>
<td>55</td>
</tr>
<tr>
<td>Ir 192</td>
<td>85</td>
</tr>
<tr>
<td>Co 60</td>
<td>140</td>
</tr>
</tbody>
</table>
Note that the maximum tangential path (or “chord length”) is substantially larger than twice the wall thickness of a pipe, even for relatively small diameter pipes. For example, a 2” schedule 80 pipe has a chord length of 35mm, which rises to almost 60mm for a 3” schedule 160 pipe.

4.2 Source to detector distances (SDD)

In radiography there are trade-offs to be made between reduced image unsharpness which requires larger source to detector distances (SDD) and shorter exposure times which require smaller SDDs but larger unsharpness. For in-service inspection, it is reasonable to permit a larger geometric unsharpness than for critical examination of new welds, since the wall loss flaws of interest are usually at least a few millimetres in size and hence give rise to more extended indications than those from cracks which are one of the main concerns in new welds.

For DWSI it is therefore usually adequate to position the source in contact with the pipe wall opposite the detector. For DWI, after much discussion, the recommendations on source to detector distances were based on geometric unsharpness criteria [7]. A specified unsharpness value in the plane of the object was used as opposed to the unsharpness in the detector plane. The unsharpness in the plane of the object was considered to be more physically meaningful than the unsharpness in the detector plane, as it is the unsharpness in the object plane that principally affects the minimum discernable detail size in the component under inspection.

The source to detector distance, SDD, needed to achieve a specified geometric unsharpness in the plane of the object (Ug') is given by:

\[
SDD = (d \cdot b) / Ug' \tag{2}
\]

Where d is the effective source size for geometric unsharpness calculations and b is the distance between the detector and the source side of the outside of the pipe. For the standard quality wall loss inspection, a maximum unsharpness of 0.6 mm was considered appropriate, and for the higher quality wall loss inspection, a maximum unsharpness of 0.3mm is recommended.

As an example, the recommended SDD for a 2” schedule pipe is about 200mm for standard quality and about 400 mm for higher quality for a typical 2 mm isotope source. The corresponding values for a 3” schedule pipe are 300mm and 600mm for standard and higher qualities respectively.

For tangential inspection with the source on the pipe centre-line, to avoid substantial distortion of the distances when the pipe wall is projected onto the detector in a “fan-beam” geometry, it is recommended that the minimum source to pipe centre distance, SPD, should be at least 3.5 times the pipe outside diameter (OD).

4.3 Image quality criteria

Experience has shown that some form of objective check on image quality is important for in-service computed radiography. Operators should be aware that very short exposure times with computed radiography can give CR images which may appear to the eye, subjectively at least, to have adequate quality when displayed on a computer monitor. However, quantitative
analysis can show that such images may have low signal to noise ratios, and hence poor sensitivity for wall loss detection by image grey level variations.

It is strongly recommended that some form of image quality indicator (IQI), or objective check on image quality is used on all CR exposures, as described below.

The following measures for CR image quality were considered:

- CR image grey level (target grey-level values)
- Image signal to noise ratio
- Single wire IQIs

4.3.1 Image grey level

Caution is needed when using CR image grey levels as a measure of image quality, as the grey level can depend on many factors including:

- Imaging plate type
- Scanner type and characteristics (log, linear etc)
- Scanner gain
- Other scanner parameters (e.g. pixel size)
- Radiation exposure incident on IP

Hence, CR image grey level in isolation is not a reliable measure of image quality without standardisation of all the associated scanner variables and IP type. Given such standardisation it should then be possible to establish that a particular grey level range will give images of sufficient quality, having made a prior assessment using either of the two methods described below. For further details on the calibration techniques required to use image grey level as a reliable quality measure see [4].

4.3.2 Signal to noise ratio

Normalised signal to noise ratio (SNR_N), as described in the CR standards EN14784 parts 1 and 2 [8], can be used to provide an objective measure of the quality of the CR image. This method can be applied to tangential radiography (see below), but the SNR_N criterion for CR image quality assessment also has a number of limitations including:

- The SNR_N value does not take any account of the radiographic contrast of the CR image.

- To derive the SNR_N value it is first necessary to derive the basic spatial resolution of the CR imaging system by analysis of the image obtained using a duplex wire IQI. Various alternative methods can be used for this analysis which may give differing values. The values may also be influenced by the presence of relatively high noise levels on CR images obtained from isotope sources.

Nevertheless, it was concluded that setting target values for SNR_N is a useful method for improving quality control of CR images. The following values are recommended:
For standard image quality, using double wall techniques, the SNR_N should be at least 50 on the pipe centre-line. Investigations by those at BAM have shown that this is equivalent to the IP5 film class, e.g. D7 film with density = 2. For the higher image quality, it is recommended that the SNR_N should be at least 80 on the pipe centre-line, which is equivalent to the IP3 film class, e.g. D4 film with density = 2.

The SNR_N method for measuring image quality can also be applied for tangential CR, provided the measurements are made on the pipe centre-line (i.e. as for DWDI) or in the free beam area, in which case the average SNR_N values obtained should be at least 70 for the standard quality and 110 for the higher quality classes of wall loss inspection.

4.3.3 IQI values

Use of IQIs is recommended for CR inspection using double wall techniques to provide an overall measure of image quality. Unlike the SNR_N measure, IQI values provide a measure of the quality of a CR image that includes the radiographic contrast. In addition, IQI values are affected by the total unsharpness of the image and the SNR_N.

IQIs can take the form of wires or step/holes. For the present work, wire IQIs were used as they are the type most commonly used in Europe for conventional film radiography of welds. Also as they need to be placed in an area of the image which is potentially subject to degradation, wire IQIs are unlikely to cause confusion with any flaws present, whereas step/hole IQIs could potentially be mistaken for, or obscure, flaws.

To establish appropriate target IQI wire values, trials were undertaken using a series of test pipes, with different diameters and wall thicknesses. The CR images were then obtained using radiographic conditions in close accordance with the recommendations for SDD and SNR_N described above. A range of commercially available scanners and IPs was also assessed.

For DWDI, the IQIs were placed on the source side of the pipe. For DWSI, the IQIs need to be placed on the detector side (between pipe wall and detector). For both DWDI and DWSI, the IQIs should be positioned close to the centre of the resulting CR image. If the IQIs are close to the edges of the images, a smaller number of wires may be detected than for centrally placed IQIs.

These measurements covered pipes with wall thicknesses in the range c. 3 mm to 22 mm. For product filled pipes, the total equivalent steel penetrated thickness was calculated using:

\[ w_{tot} = w_s + \frac{ID}{f} \]  

(3)

where \( w_s \) is the steel penetrated thickness, ID is the pipe internal diameter and \( f \) is a factor representing the lower attenuation of the product compared with steel. Estimates for \( f \) from the present work are \( \sim 9 \) for water (based on direct measurements) and \( \approx 11 \) for oil (based on the measured value for water with appropriate allowance for the difference in density only).

A degree of variability in the smallest diameter IQI wire visible was found. Recommended values were then generally taken from the lower bound of the measured values. For the 2\" schedule 80 pipe mentioned in previous sections, IQI wire 9 is needed for wall loss radiography, compared with W13 for Class A weld radiography.
For further details on recommended IQI values for DWSI, and for Se75 sources, see [4]. For pipes that are insulated, it is not generally possible to place IQI wires on the source side of the pipe, so the recommended IQI values for DWSI may be used, in conjunction with measurement of SNR_N on the pipe centre line.

4.4 Exposure guidelines

4.4.1 Double-wall techniques

CR plates have a wide tolerance or latitude to variations in exposure times. However, experience has shown that using very short exposure times will result in poor image quality, and hence low sensitivity to wall loss with the DWDI and DWSI techniques. Correspondingly lower wall thickness measurement accuracies can be anticipated with the tangential method for short exposure time images.

To avoid these issues, the exposures times for computed radiography should be sufficient to give CR images with the required quality, as described in Section 4.3.

To estimate the required exposure times, the following approximate formula may be used:

\[
E_w = 2.4 \times 10^{-3} E_0 \exp \left( + \mu w_{tot} \right) \frac{SDD^2}{S}
\]

(4)

Where

- \( E_w \) is the exposure time in sec for penetrated thickness \( w \).
- \( E_0 \) is the exposure needed to achieve the required SNR_N value for zero penetrated thickness in units of Ci.min @ 500mm.
- \( S \) is the source strength in Ci.
- \( SDD \) is the source to detector distance in mm.
- \( \mu \) is the measured effective material attenuation coefficient (~0.04 /mm for Ir 192 and ~0.08 /mm for Se 75).
- \( w_{tot} \) is the total steel equivalent penetrated thickness in mm, including any product in the pipe (see equation 3).

Note that if the exposure, \( E_0 \), is expressed in units of gBq. sec @ 1000mm, then the constant in equation (4) is 2.7 x 10^{-8}.

The HOIS CR trials have shown that the exposure times required to obtain the recommended SNR_N values on the pipe centre-line depend on the imaging plate and scanner, as illustrated in Figure 1. This shows SNR_N values obtained as a function of exposure for five different commercially available CR scanners and imaging plates.
Figure 1. Measurements of normalised signal to noise ratio as a function of exposure incident on the IP, for five different CR scanner/IP combinations.

For the standard image quality class (SNR_N ≥ 50 on the pipe centre-line), exposures E₀ in the range ∼3 - 15 Ci.Min @ 500mm were measured in the HOIS CR trials, depending on the CR scanner and imaging plate being used. For the higher image quality class (SNR_N ≥ 80 on the pipe centre-line), the exposures E₀ were of course higher, being in the range ∼10 - 30 Ci.Min @ 500mm.

Significantly longer exposures may be needed if high-resolution (“blue”) imaging plates intended for weld inspection are used for in-service inspection.

4.4.2 Tangential technique

For tangential radiography, the times given above for DWDI can generally be used as a guide. It is also important to ensure that the scanner gain/sensitivity setting is adjusted so that the unimpeded radiation beam outside the pipe wall is not saturated, which will cause “burn-off” and errors in wall thickness measurement.

4.4.3 Scanner gain

The HOIS CR trials have shown conclusively that altering the scanner gain or sensitivity (speed class) usually has no significant effect on SNR_N, for a particular scanner/IP and exposure time. Only increasing the radiation dose or exposure incident on the IP will increase the number of photons detected by the IP, and hence improve image quality.

Saturation can also be a significant issue, especially for scanners having linear responses to radiation intensity. For tangential CR, the free-beam areas outside the image of the pipe should be unsaturated, since saturated images would cause “burn-off” and errors in wall thickness measurement (these errors will lead to measurements systematically less than the true values). To minimise the risk of saturation, especially on thicker walled and/or larger diameter pipes, use of low scanner gains/sensitivities is recommended.
5. Blind trial results

In 2003, an initial DWDI CR blind trial was performed on a set of 6” nominal bore pipes, with two different schedules (nominal wall thickness values of 7.1mm and 14.3mm). These pipes were straight, about 2m long and contained a number of internal wall loss flaws, with a wide range of morphologies. These flaws were not machined but had been introduced artificially using an accelerated corrosion process.

The overall probability of detection (POD) achieved in this 2003 trial was only about 60%, which was considered disappointing, given the flaw characteristics, including their through-wall extent. A follow-up investigation suggested that the images obtained may have been of relatively low quality, as a result of an inspection procedure that was not sufficiently developed for the DWDI technique used.

During the development of the HOIS recommended practice [4] a repeat blind trial on a similar set of specimens was undertaken in 2007. In this repeat trial, the DWSI technique was used to reduce exposure times and the CR was performed in accordance with the recommendations contained in an early draft of the RP, which were not substantially different from those in the final published version.

The POD achieved in this repeat blind trial was about 98%, which was a significant improvement on the original value of ~60%. This demonstrated that CR performed in accordance with the recommendations contained in [4] is capable of a high detection performance for simulated realistic wall loss flaws in pipes.

6. Conclusions

There is increasing application of computed radiography (CR) to in-service inspection of pipes within the oil and gas industry. Typically the components inspected are small diameter pipes, for which CR can provide an effective technique for both detection and sizing (via the tangential technique) of wall loss flaws, such as corrosion or erosion.

However, the technology associated with CR is substantially more complex than film, and, in the absence of any internationally recognised standards for in-service radiographic inspection, the quality of the resulting CR images can be variable.

In a major project, which has included a significant number of experimental trials using state of the art CR equipment, the HOIS JIP has developed a recommended practice for this application, with the aim of providing guidance to improve the quality control of the results obtained.

The key recommendations concerning source selection, source to detector distances, and image quality criteria have been summarised in this paper. For full details, the reader is referred to the published recommended practice which can be freely downloaded from www.hoispublications.com.

These recommendations have been validated by means of a blind experimental trial which showed a greatly improved detection performance compared with that achieved previously in an earlier trial carried out prior to the formulation of this document.
A draft two part EN Standard based on these recommendations should be issued for public comment shortly.

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3. For more details on the HOIS joint industry project, see http://www.hois2000.com.


8. ‘Non-destructive testing – Industrial computed radiography with phosphor imaging plates’, Parts 1 and 2. EN 14784-1, -2.