

HOIS/NZTC Guidance on inspection of uninsulated external corrosion scabs

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Executive Summary

External corrosion of carbon steel pipework is a major problem for oil and gas facility owners and has led to loss of containment. As external degradation occurs, corrosion product or scale usually builds up on the affected components. Removal of corrosion product by blasting pressurised live process components has an associated hazard of loss of containment.

The requirement considered in this document is determination of the remaining ligament under the corrosion product or scab, without the potentially hazardous removal of this material. As it is generally not possible to propagate ultrasound through corrosion product, the presence of the scab renders the area of corrosion inaccessible and standard 0° pulse-echo methods are not applicable for measurement of the remaining thickness in badly corroded areas.

The present document provides guidance on the inspection of uninsulated external corrosion scabs, based on the results from four series of trials performed in HOIS projects and other information obtained during these HOIS projects.

This guidance aims to provide operators and NDT service providers with current relevant information on the available NDT methods for in-service determination of the minimum remaining ligament for external corrosion scabs on live lines where it is hazardous to remove the scale/corrosion product to obtain direct access to the underlying steel surface. This should lead to a more consistent approach across the industry.

The available scab height and wall loss data shows wide variations in the values for service-induced corrosion, without any information on the most reliable value to use. The available values suggest however that a mostly conservative “rule of thumb” value to use would be to assume that the wall loss is equal to the scab height, i.e. considering a 1:1 ratio. It should be recognised that the data set on which this is based is limited and is thought to be primarily based on results from offshore, North Sea operations. Hence the 1:1 ratio can not be taken as universally conservative and should only be considered, as appropriate, as a basis for estimates where the resulting wall loss is not approaching an integrity limit and there is also good evidence that corrosion product has not been lost from the scab.

Accurate measurement of the remaining wall thickness under scabs is a challenging requirement for NDT methods, as the presence of the scab material makes the outer steel surface inaccessible. In addition, the scab itself can take many different shapes, with varying circumferential and axial extents and profiles, depending on the time over which it has developed and the corrosion mechanisms.

Factors that influence the applicability of NDT methods for scab minimum ligament determination include the following:

- Pipe diameter and wall thickness
- Component geometry
- Extent of the corroded area in the axial and circumferential directions
- Accessibility to the corroded area and space around it
- Surface condition surrounding the corroded area
- Morphology of the corrosion, especially the presence of highly localised pitting

The methods included in the HOIS trials that gave the highest sizing accuracies (of around $\pm 10\%$ of the uncorroded wall thickness), under appropriate conditions, in test components lacking highly localised corrosion, were:

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- Tangential Computed Radiography (for thin-walled, small bore pipes only, but note limited circumferential coverage and issues stated in ISO 20769 part 1),
- QSR1 for pipes with wall thicknesses in the range 6-13mm, and diameters in the range 6" – 24".
- Multi-skip/M-skip® for thick-walled pipes only.

The ranges of applicability of these methods in terms of pipe wall thickness and diameter are largely complementary, so that at least one of these methods is available for the majority of pipes used in the oil and gas industry. The eddy current based methods trialled gave somewhat lower sizing accuracy, with a tendency to undersize due to sensor footprint averaging effects. However, on one set of pipes with realistic but simulated areas of wall loss, the CWT values provided by the Eddyfi Lyft pulsed eddy current equipment provided a comparable level of accuracy.

Previous internal UT benchmarking information from one set of ex-service pipes has shown the unexpected presence of some highly localised pitting, superimposed on more general areas of wall loss. These pits, which had average axial/circumferential extents of only ~5mm presented substantial challenges to all the currently available NDT methods. This was caused by the limited spatial resolution of these methods, which makes the localised pits difficult to detect and hence affects the ability to measure the actual minimum ligament thickness. The result can be a tendency to undersize the remaining ligament thickness.

The presence of these localised pits was not visually apparent from an external examination of the scab, and their frequency of occurrence in pipework within the energy industry is unknown, as are the corrosion conditions leading to their formation. The possibility that these localised pits might be present increases the uncertainty in the values for remaining ligament derived by current NDT methods.

In recent trials based on a small sample size, it was demonstrated that double-wall radiography is a method with potential for use as a complementary screening tool for determining the possible presence of localised pits under external corrosion scabs. If double wall radiography shows no evidence of isolated localised pitting, this would give increased confidence in the reliability of the NDT methods for determination of the remaining ligament. Conversely, if evidence of localised pitting is apparent on the radiographs, this would increase the likelihood that the results from the NDT method significantly undersize the wall loss present.

The applicability of 3-D laser scanning and photogrammetry to characterise scab height/topography was also investigated and both were found to be a useful tool when interpreting radiographs from an external corrosion scab, where irregularities in the external scab profile, such as selective spallation of areas of the scab, can complicate radiograph interpretation.

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1 Introduction

External corrosion of carbon steel pipework is a major problem for oil and gas facility owners and has led to loss of containment. As external degradation occurs, corrosion product or scale usually builds up on the affected components. Removal of corrosion product by blasting pressurised live process components has an associated hazard of loss of containment.

The requirement considered in this project is determination of the remaining ligament under the corrosion product or scab, without the potentially hazardous removal of this material. As it is generally not possible to propagate ultrasound through corrosion product, the presence of the scab renders the area of corrosion inaccessible and standard 0° pulse-echo methods are not applicable for measurement of the remaining thickness in badly corroded areas.

An initial 3-year HOIS project C12-01, involving extensive trials of NDT techniques for inspection of externally corroded un-insulated pipes with the corrosion product in-situ, was completed early in 2015 [1]. Although project C12-01 involved a significant number of trials on a variety of specimens, it was found that there was no universally applicable technique capable of accurately sizing the remaining wall thickness of externally corroded areas on all pipe diameters and wall thicknesses. The morphology of the external corrosion was also found to affect the results obtained with many of the techniques.

Given the widespread occurrence of externally corroded pressurised components within the oil and gas industry, at the March 2015 meeting the HOIS members supported a further project (C15-02) on this challenging area of NDT, with the objective of performing further trials of techniques that showed promise from the earlier trials and any other developmental techniques that had not been included in the earlier project. The main objective of C15-02 was to assess further the performance and capabilities of two methods that had shown promising results in the previous trials [2].

In March 2017, a further ambitious and strategic HOIS project (C17-01) on the inspection of external corrosion with and without insulation was approved. This project was supported by The Oil and Gas Technology Centre (now the Net Zero Technology Centre) and was designed to develop and focus the HOIS resources and capabilities for conducting rigorously controlled independent evaluation trials and to compare different inspection methods for these challenging problems.

In addition to the CUI trial programme, project C17-01 included manufacture of additional test samples to provide further examples of simulated external corrosion scabs, to be followed by additional trials on these test samples and some of the earlier components, particularly the ex-service ones. Project C17-01 also included the in-house design and build of an internal UT scanner for corrosion mapping deployed from the inside of a pipe. The probe, scanning, data collection and processing were in full accordance with the HOIS recommended practice for precision UT thickness measurements [3]. This allowed accurate measurements of remaining thickness to be made, and hence allowed benchmarking of the ex-service samples with external corrosion scabs to allow comparisons to be made with the results of NDT trials conducted within the present project, and those performed in the earlier project C15-02.

The C17-01 trial report [4] gave details of the samples used for the trials with a description of the benchmarking techniques used to derive accurate measurements of remaining wall thickness/wall loss for the corroded areas. The trials comprised further M-skip scans of the additional manufactured components, dual frequency eddy currents, pulsed eddy currents (PECT from Maxwell NDT) and the GUL QSR1 system. An analysis of the trial results was reported, as well as any issues encountered during the trials. A guidance document for the

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inspection of un-insulated external corrosion scabs was developed in this project, informed by all the HOIS trials undertaken since the first trials in project C12-01.

The current HOIS project (C19-01) has sought to evaluate the effectiveness of selected NDT techniques in determining the minimum remaining ligament under scabs where the corrosion includes localised pitting [5]. Two pipes were manufactured for this study, each containing CNC-machined areas of wall loss containing localised pitting but with differing types of morphology. This project was also supported by The Oil and Gas Technology Centre (now the Net Zero Technology Centre).

In addition to these recent trials, HOIS performed a series of preliminary tests to investigate the feasibility of using double-wall radiography for use as a complementary screening tool for determining the possible presence of isolated pits under external corrosion scabs [6]. The applicability of 3-D laser scanning and photogrammetry to characterise the height/topography of the scabs was also investigated as a means for assisting with the interpretation of the radiographs.

The present document provides updated guidance on the inspection of uninsulated external corrosion scabs, based on that developed in project C17-01 and the trial results from the four HOIS projects on external corrosion outlined above (C12-01, C15-01, C17-01 and C19-01), and other information obtained during these HOIS projects.

This document gives in Section 5 and Appendix 1, a summary of relevant information on scabs within the oil and gas industry. The main NDT methods currently available are summarised in Section 6 and Appendix 2. Where available, performance and reliability information obtained from the HOIS scab trials (as summarised in Section 7) is included in Appendix 2. Section 8 provides guidance on application of the methods depending on the inspection requirements, including summary tables of method applicability.

2 Scope

This guidance is intended for areas of external corrosion that have been located by other means (e.g. visual inspection) and for which removal of the corrosion product or scale is considered to be hazardous, due for example to the component being in operation ('live-line').

Hence the requirement for these areas of external corrosion is taken to be measurement of the remaining ligament by methods that do not involve removal or disturbance of the corrosion product or scale. For the purposes of these guidelines, it is however assumed that direct access can be obtained to the outside of the corroded area, which is not made inaccessible by the presence of obstructions such as clamps, pipe supports, saddles etc.

The component material is limited to carbon steel and the degradation type is limited to loss of wall due to corrosion. Other forms of degradation such as cracking are beyond the scope of the present document.

3 Abbreviations and symbols

Term/symbol	Meaning
AWT	Averaged Wall Thickness is used in some PEC units, where the average of the remaining wall thickness is determined over the sensor footprint.
CR	Computed Radiography, which involves usage of a flexible imaging plate (IP) which is first exposed to radiation which generates a latent image and then scanned using a laser scanner to provide a digital radiograph that is displayed using a computer.
CWT	Compensated Wall Thickness has been developed by Eddyfi and uses a proprietary algorithm for correcting the remaining wall thickness values for the effects of sensor footprint averaging.
DDA	Digital detector array. Used for digital radiography, a DDA is usually a 2-D array detector that provides a real-time or near real-time digital radiograph which is displayed on a computer monitor.
EMAT	Electromagnetic acoustic transducer
GWT	Guided Wave Testing
ID	Pipe inner diameter
95% LUS	95% LUS is a statistical parameter. It is a 95% safety limit against undersizing. When the value of this parameter is added to a reported size from an NDT inspection, then the resulting size has a 95% confidence of not being undersized (see Section 5.6.5.2 of Burch, 2015b and references therein).
Multi-skip/M-skip	A pitch-catch ultrasonic inspection method using vertically polarised shear waves (SV) and involving multiple reflections or skips off the component ID and OD.
OD	Pipe outside diameter
PA	Phased Array
QSR-1	Quantitative Short-Range guided wave inspection system developed by Guided Ultrasonics Ltd (GUL).
R	Correlation coefficient. Used here to assess correlation between two sets of values. A value of 1 indicates perfect correlation/agreement. A value of zero indicates no correlation.
RMS	Root-mean-square
σ	Standard deviation – in this document refers to the standard deviation of the differences between the sizing values from an NDT method and the corresponding benchmark values.
SV	Vertically polarised shear waves
W_{max}	Maximum steel equivalent penetrated thickness (for radiography)
WT	Uncorroded wall thickness

4 Standards

ASME BPVC-V 2021 Edition, July 2021 Article 21. Pulsed Eddy Current (PEC) Technique For Corrosion Screening

ISO 20769:2018 Non-destructive testing. Radiographic inspection of corrosion and deposits in pipes by X- and gamma rays. Part 1: Tangential radiographic inspection Part 2: Double wall inspection.

ISO 20669:2017 Non-destructive testing – Pulsed eddy current testing of ferromagnetic metallic material components

5 Scabs in the oil and gas industry

Available information on the external appearance of scabs, and their characteristics (including morphology) is summarised in Appendix 1. Included in this appendix is a compilation of available values for the ratio between scab height and wall loss.

On the basis of available information, it is unclear how the ratio between scab height and wall loss is influenced by the corrosion conditions, and hence it is not possible to predict what an appropriate value would be for a particular corroded area.

The available scab height and wall loss data does however suggest that a conservative “rule of thumb” value to use would be to assume that the wall loss, w , is equal to the scab height, h (see Figure A1-5 for definition of these values), but only provided there is good evidence that the corrosion product has not been lost (e.g. the coating is still mainly intact).

Information is also given on the morphologies of the wall loss for scabs on several examples of ex-service pipes provided by HOIS members. Internal UT scans of scabs on two different pipe sets, have shown significant differences between the morphologies of set 1 compared with set 2.

It is particularly significant that examples of corroded areas in one of these pipe sets were found to contain highly localised, and often isolated pits, superimposed on generalised wall loss. These localised pits had significant additional wall losses of ~3-5mm compared with the surrounding corrosion, over circumferential/axial extents of ~5-15mm.

In comparison, the scabs in the other pipe set did not contain these highly localised pits and had irregularities in wall loss over significantly larger length scales (typically a few tens of millimetres, although this varied from one scab to another).

The presence of highly localised pitting presents significant challenges for any NDT methods that may be used to estimate the remaining wall thickness under these scabs, due to the normally limited spatial resolution of the NDT methods. This can lead to significant sensor footprint averaging effects, and/or failure to detect the fine pitting, both of which effects may lead to significant underestimates of the wall loss/severity of the corrosion. As a result, the latest HOIS trial programme focussed on the examination of scabs with localised pitting [5].

6 NDT methods currently available for scab inspection

Appendix 2 summarises current NDT methods that can, under appropriate conditions, provide quantitative measurements of the remaining wall thickness under areas of external corrosion covered with corrosion product.

7 Trials of NDT methods for scab inspection

Within the HOIS JIP there have been four sets of trials of NDT methods for scab inspection [1][2][4][5]. The trials were generally conducted blind and were based on both ex-service and manufactured components. Most trials were in the HOIS NICE facility, although in a few cases the trials were conducted elsewhere. The following NDT methods were included:

1. Pulsed Eddy Current (Applus RTD Incotest, Shell PEC and Eddyfi Lyft, Maxwell PECT)
2. Digital tangential radiography (HOIS multi-vendor trials)
3. Medium range guided waves (GUL, QSR1)
4. Dual frequency Eddy Currents (ETHerNDE)
5. Multi-skip/M-skip® ultrasonic method (ESR)
6. Guided and SH-wave EMATs for screening (Baugh & Weedon & Sonomatic)
7. Back-scatter radiography (developmental) (Inversa Systems)
8. Pulsed X-ray radiography (Bilfinger)

Where available, for each NDT method a summary of the results from the trials are given in Appendix 2.

8 Guidance on selection of NDT methods for scab inspection

8.1 Overview of methods

Detailed information is given on NDT methods for scab inspection in Appendix 2.

The applicability of an NDT method for scab inspection depends on many factors including:

- Radiation hazards - can they be adequately managed?
- Does the method need to be applicable to pressure vessels?
- Does the inspection need to cover geometry changes (tees, supports, connections etc.)?
- Are the pipe diameter and wall thickness within the applicability limits of the methods?
- The extent and morphology of the corroded area.
- The possible presence of highly localised fine pitting superimposed on more generalised wall loss.

8.2 Methods for quantitative sizing of remaining ligament under scabs

Table 8-1 gives a summary of the information contained in Appendix 2 in a format that allows the main factors listed above to be considered for all methods deemed to have potential for quantitative sizing of the remaining ligaments under scabs. Note also the table footnotes.

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Table 8-1: Summary of applicability of current methods for scab NDT

Method	Pipe OD	Pipe WT	Complex geometry applicability	Vessel applicability	Highly localised pitting	Sizing accuracy from HOIS trials ¹	Other constraints ²
Visual/Scab height	Any	Any	High	Y	N	Low	Scab height to wall loss ratio varies widely.
Dual frequency Eddy currents	≥ 1"	≥ 3mm	Medium	Y	N	Medium ³	Need to maintain a constant offset between the probe and the component surface. Variations in magnetic properties of scab material.
Multi-skip/M-skip [®]	≥4"	~ 15 – 30mm	Low	Y	N	High	Scab extent < 18WT; adequate surface condition around scab needed for UT probes.
PEC	≥ 2" ⁴	3 – 102mm ⁵	Medium	Y	N	Medium ⁶	Magnetic properties of scab material, morphology of corrosion. Averages over sensor footprint area, so can undersize localised areas of corrosion.
QSR1	6" - 24"	6-13mm (nominal)	Low	N	N	High	At least 120° of good material needed at same axial location as scab, to allow scanner wheels and probes to be in contact with the pipe surface.
Radiography (tangential)	For Ir192, max penetrated steel thickness <80mm – see also Figure 8-1.		High	N	N ⁶	Medium ⁷	Ionising radiation hazard, morphology of the corrosion.
Radiography (double wall)	Any	45mm for Ir 192, without liquid in pipe (improved technique).	High	N	Y ⁷	N/A ⁸	Ionising radiation hazard. Liquid in pipe reduces contrast of radiograph, and therefore the sensitivity to localised pitting. Scab spallation would complicate interpretation of radiograph.

Footnotes

- ¹ Excluding scabs with highly localised pitting
- ² In addition to the factors listed, all methods are affected by corrosion morphology, by varying amounts, especially the presence of highly localised pitting, where present
- ³ Accuracy reduced for complex scab morphology, due to large sensor size
- ⁴ Minimum inspectable pipe OD may differ between manufacturers. Refer to manufacturer’s literature for more information.
- ⁵ Maximum wall thickness is dependent upon probe size and lift off. Refer to manufacturer’s literature for more information.
- ⁶ On one set of scabs, sensor footprint averaging effects led to ~20% undersizing for AWT values; improved accuracy for CWT (Lyft) and DWT (Incotest) measurements
- ⁷ Tangential radiography becomes unreliable for localised pitting (see ISO 20769:1 and Ref. [1]).
- ⁸ Double radiography is a method with potential for screening for the possible presence of localised corrosion pits, which if present, are likely to reduce the accuracy of the sizing methods given in this table. Double Wall radiography does not in itself give any through-wall sizing information.

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Based on the information in the table above, Figure 8-1 shows the applicable pipe OD and WT values for all the NDT methods except PEC and dual frequency EC. Given that PEC and dual frequency EC are applicable for inspection of pipes with similar outside diameters and wall thicknesses, a graphical representation was not produced.

The white areas in this figure represent pipes for which none of the NDT methods are currently applicable, whereas the coloured or shaded regions represent where the different methods can be applied, which may overlap in some cases.

Examination of Figure 8-1 shows that one or more NDT methods are applicable to the great majority of combinations of pipe OD and WT. Note also that those methods shown as being applicable to pipe diameters up to the maximum of 800mm given in the figure or in Table 8-1 are also applicable to larger diameter components, including vessels with higher ODs.

The three methods shown in Figure 8-1 (QSR1, Tangential RT and Multi-skip) are mainly complementary since their ranges of applicability only overlap slightly. Tangential RT in accordance with ISO 20769-1 should be used for small-bore pipes and some with larger diameters but thin walls (maximum penetrated thickness at the tangent position of ~80mm if using an Ir 192 source). QSR1 covers larger diameter thinner walled pipes up to 24", while Multi-skip is applicable to the thicker-walled pipes (those with wall thicknesses greater than about 15mm), without any limit on OD (applicable to vessels as well as large diameter pipes). The PEC method covers most pipes with wall thickness up to 16mm (larger wall thicknesses may also be examined but only by means of larger sensors that lead to increased sensor footprint averaging effects). The Dual frequency EC method can, in principle, be applied to all components with diameters of at least 1", although the smallest diameter it has been trialled on is 6".

In considering the most effective method for quantitative sizing of scabs to use for a particular scab, the information given in Table 8-1 and Appendix 2 should be considered carefully in addition to the applicability data for OD and wall thickness given in Figure 8-1.

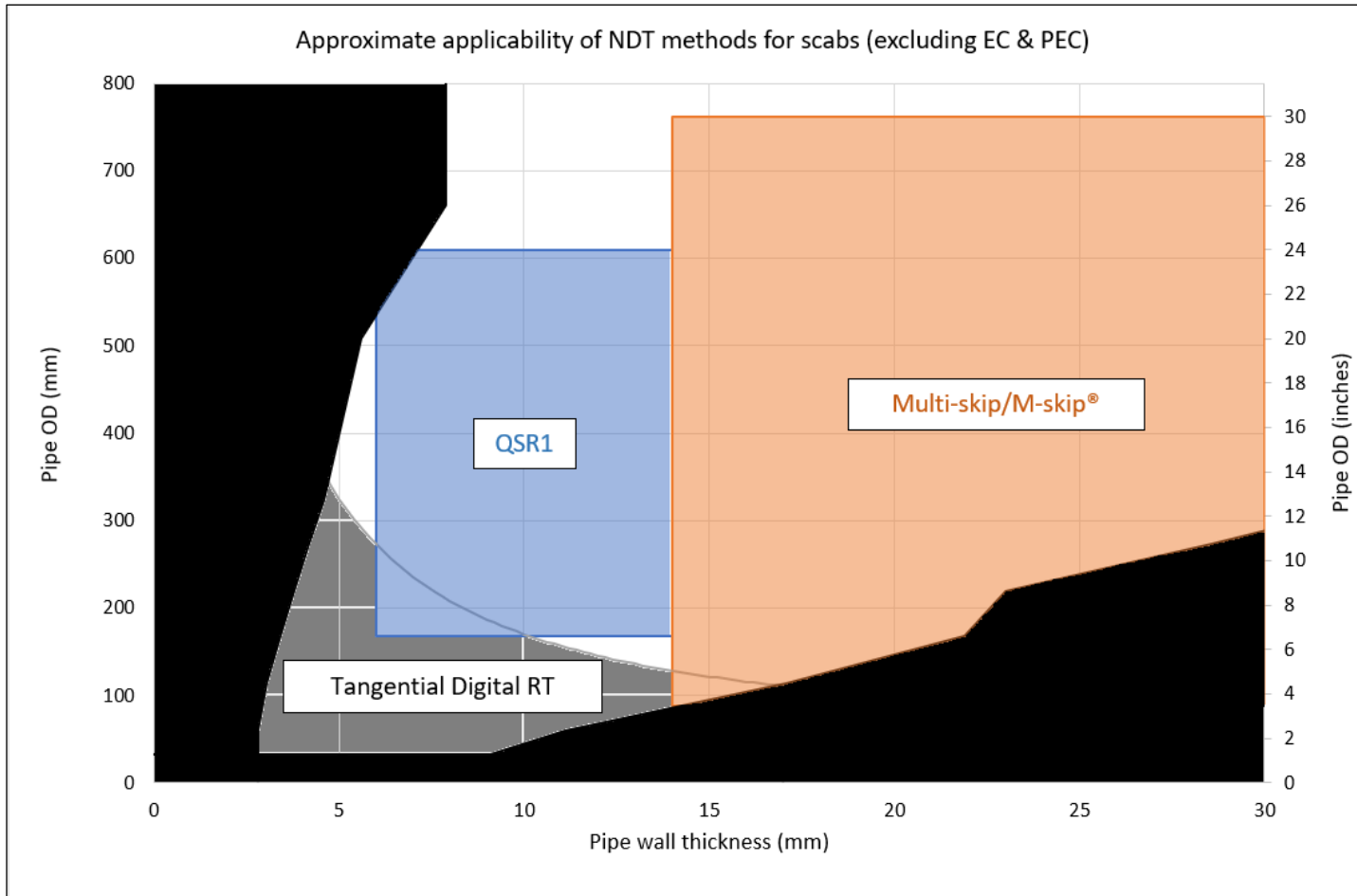


Figure 8-1: Approximate representation of the applicability of different NDT methods for scab sizing, excluding dual frequency EC & PEC, for different pipe diameters and wall thicknesses. The black areas represent pipes that are thinner walled or thicker walled than those normally manufactured (sch 10 used as lower limit and sch XXS or sch 160 as upper limit).

8.3 Localised or fine pitting

8.3.1 Presence and likely effects on sizing methods

One set of ex-service pipes included in the HOIS trial programmes showed the unexpected presence of highly localised groups or clusters of multiple pits, superimposed on more general areas of wall loss (see Appendix A1.3). The individual pits within these groups were detected by internal UT scanning and were found to have average axial/circumferential extents of only ~5mm, with depths of up to 2-3mm [4].

The presence of these localised pits was not visually apparent from an external examination of the scab, and their frequency of occurrence under external corrosion scabs within the energy industry is unknown, as are the corrosion conditions leading to their formation.

The potential that these localised pits are present may increase the uncertainty in the values for remaining ligament derived by current NDT methods since the spatial resolution of these methods is generally substantially lower than the dimensions of the individual pits in the clusters. This limited resolution, combined with sensor footprint averaging effects, is likely to make the localised pits difficult to detect and may cause increased undersizing of the wall loss.

8.3.2 HOIS trials

The current HOIS project (C19-01) sought to evaluate the effectiveness of selected NDT techniques in determining the minimum remaining ligament of scabs containing localised pitting [5]. Two pipes were manufactured for this study, each containing CNC-machined areas of wall loss containing localised pitting but with differing types of morphology, see Figure 8-2.

Both pipes had wall loss with morphologies based upon corrosion found in ex-service pipes. For one pipe, the areas of wall loss were characterised by multiple localised pits, superimposed on more general areas of wall loss. These were direct replicas of examples of corrosion scabs found in ex-service pipes, although due to limitations of the modelling and CNC processes, it was not possible to replicate some of the finest detail found in these pipes.

For the other pipe, the underlying morphology was different with larger scale variations in wall loss, based on a different set of ex-service pipes. Single localised pits were then added to these CNC areas using mechanical methods.

For both pipes, to simulate the presence of natural corrosion product, the areas of wall loss were covered with synthetic scab material that consisted of magnetite granules (which is ferrimagnetic) embedded in modelling clay.

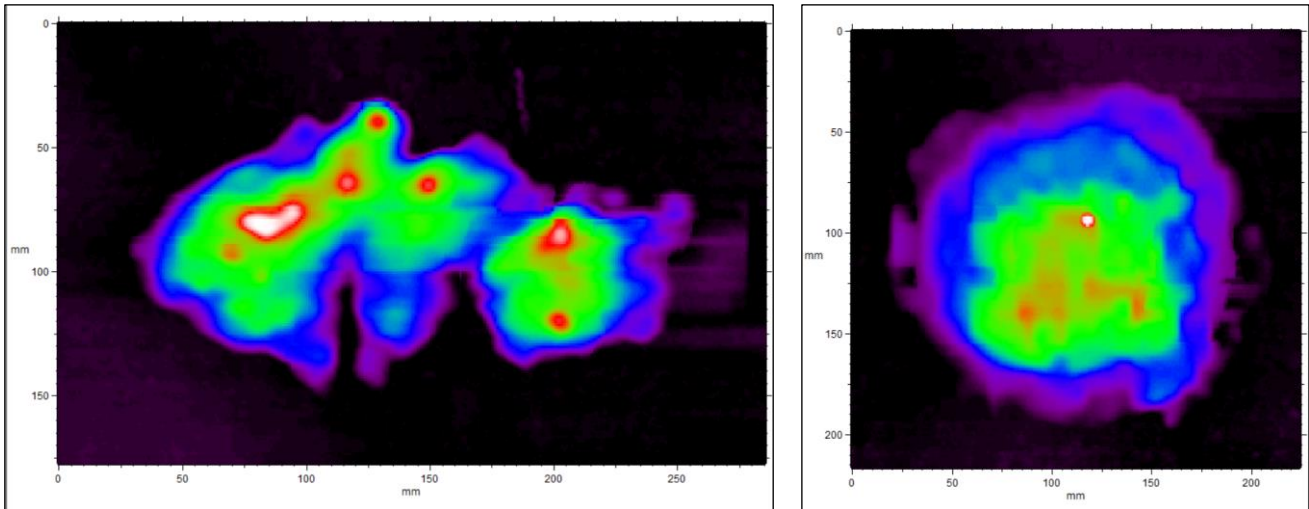


Figure 8-2: Examples of morphologies of the CNC areas of wall loss introduced into the test pipes. Left – multiple localised pits superimposed on a larger scale area of wall loss. Right – area with larger scale wall loss, with a single localised pit introduced.

Of the different methods trialled, QSR1 from GUL showed the smallest overall differences from the benchmark values for both pipe samples. M-Skip exhibited similar results to QSR1 for the pipe with the multiple localised pit clusters, but larger differences on the sample containing the additional single localised pits. This may have been caused either by the lack of detection of the additional pits, or the lack of both axial and circumferential measurements for three of the four scabs. Of the electromagnetic methods, the PECA-HR (with CWT) exhibited smaller differences from the benchmark when compared with the Maxwell PECT (with AWT) values. The dual frequency EC method was generally comparable to the PECA-HR results.

Generally, it is likely that most, if not all, of the methods trialled failed to detect the additional single localised pits, which resulted in the observed undersizing. However for the pipe containing areas with multiple localised pits, the mean undersizing with QSR1 and M-skip was reduced. In addition, the mean undersizing for the eddy current methods was reduced for the pipe with the multiple localised pits, an effect which may be attributed to reduced sensor footprint averaging effects, compared with the single localised pits.

8.3.3 Double wall radiography for detection of presence of localised pits

In this trial programme, double-wall radiography was also investigated as a method with potential for use as a complementary screening tool for determining the possible presence of localised pits under external corrosion scabs.

The basis of this method is that the isolated fine pitting will cause less radiation attenuation than the surrounding areas and that this will then be visible as areas (indications) on the corresponding radiographs. Knowledge of the presence or absence of isolated pitting from double wall radiography could then potentially be used to assess the likely uncertainty in the results from other NDT methods that are known to undersize the wall loss when isolated pits are present. If double wall radiography shows no evidence of isolated localised pitting, this would give increased confidence in the reliability of the NDT methods for determination of the remaining ligament. Conversely, if evidence of localised pitting is obtained on the radiographs, this would increase the likelihood that the results from the NDT method significantly undersize the wall loss present.

In recent trials [6], based on a small sample size, it was demonstrated that the use of double wall radiography has potential for this purpose, but more work is required to determine whether it would be effective in the field. The applicability of 3-D laser scanning and photogrammetry to characterise scab

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height/topography was also investigated and both were found to be a useful tool when interpreting radiographs from an external corrosion scab.

9 Conclusions

This guidance document aims to provide operators and NDT service providers with current relevant information on the available NDT methods for in-service determination of the minimum remaining ligament for external corrosion scabs on live lines where it is hazardous to remove the scale/corrosion product to obtain direct access to the underlying steel surface. This should lead to a more consistent approach across the industry.

The available scab height and wall loss data shows wide variations in the values for service-induced corrosion, without any reliable information on the most reliable value to use. The available values suggest, however, that a mostly conservative “rule of thumb” for estimates would be to assume that the wall loss is equal to the scab height (see Figure A1-5 for definition of these values), i.e. considering a 1:1 ratio. It should be recognised that the data set on which this is based is limited and is thought to be primarily based on results from offshore, North Sea operations. Hence the 1:1 ratio can not be taken as universally conservative and should only be considered, as appropriate, as a basis for estimates where the resulting wall loss is not approaching an integrity limit and there is also good evidence that corrosion product has not been lost from the scab.

Accurate measurement of the remaining wall thickness under scabs is a challenging requirement for NDT methods, as the presence of the scab material makes the outer steel surface inaccessible. In addition, the scab itself can take many different shapes, with varying circumferential and axial extents and profiles, depending on the time over which it has developed and the corrosion mechanisms.

Factors that influence the applicability of NDT methods for scab minimum ligament determination include the following:

- Pipe diameter and wall thickness
- Component geometry
- Extent of the corroded area in the axial and circumferential directions
- Accessibility to the corroded area and space around it
- Surface condition surrounding the corroded area
- Morphology of the corrosion, especially the presence of highly localised pitting

The methods included in the HOIS trials that gave the highest sizing accuracies (of around $\pm 10\%$ of the uncorroded wall thickness), under appropriate conditions, in test components lacking highly localised corrosion, were:

- Tangential Computed Radiography (for thin-walled, small bore pipes only, but note limited circumferential coverage and issues stated in ISO 20769 part 1).
- QSR1 for pipes with wall thicknesses in the range 6-13mm, and diameters in the range 6” – 24”.
- Multi-skip/Multi-skip for thick-walled pipes only.
- Eddyfi Lyft PEC with CWT.

The ranges of applicability of these methods in terms of pipe wall thickness and diameter are largely complementary, so that at least one of these methods is available for the majority of pipes used in the oil and gas industry. The eddy current based methods trialled gave somewhat lower sizing accuracy, with a tendency to undersize due to sensor footprint averaging effects. However, on one set of pipes with realistic but simulated areas of wall loss, the CWT values provided by the Eddyfi Lyft pulsed eddy current equipment provided a comparable level of accuracy.

Recent internal UT benchmarking information from one set of ex-service pipes has shown the unexpected presence of some highly localised pitting, superimposed on more general areas of wall loss. These pits, which had average axial/circumferential extents of only ~5mm presented substantial challenges to all the

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currently available NDT methods. This was caused by the limited spatial resolution of these methods, which makes the localised pits difficult to detect and affects the ability to measure the actual minimum ligament thickness. The result can be a tendency to undersize the remaining ligament thickness.

The presence of these localised pits was not visually apparent from an external examination of the scab, and their frequency of occurrence in pipework within the energy industry is unknown, as are the corrosion conditions leading to their formation. The possibility that these localised pits might be present increases the uncertainty in the values for remaining ligament derived by current NDT methods.

In recent trials [6], based on a small sample size, it was demonstrated that double-wall radiography is a method with potential for use as a complementary screening tool for determining the possible presence of localised pits under external corrosion scabs. If double wall radiography shows no evidence for isolated localised pitting, this would give increased confidence in the reliability of the NDT methods for determination of the remaining ligament. Conversely, if evidence of localised pitting is obtained on the radiographs, this would increase the likelihood that the results from the NDT method significantly undersize the wall loss present.

The applicability of 3-D laser scanning and photogrammetry to characterise scab height/topography was also investigated and both were found to be a useful tool when interpreting radiographs from an external corrosion scab, where irregularities in the external scab profile, such as selective spallation of areas of the scab, can complicate radiograph interpretation.

10 Acknowledgements

HOIS members are thanked for their contributions and the NZTC (formerly the OGTC) are thanked for co-funding the most recent projects.

Those companies that participated in the various HOIS external corrosion (scab) trials that took place within four separate projects since 2012 are thanked for their contributions. These included Baugh & Weedon, Bilfinger, Eddyfi, ETherNDE, Inversa Systems, Guided Ultrasonics Ltd, Maxwell NDT, Oceaneering and Sonomatic. The contributions made by the participants in HOIS digital radiography trials are also acknowledged, especially the equipment vendors (Duerr NDT, FujiFilm and GE) and ApplusRTD who hosted some of these trials and providing all the necessary facilities.

The project champions Billy Mackay (Total) and Dennis Zaal (Shell) provided useful guidance and support throughout the duration of the most recent project. The contributions from the project champions from the previous HOIS projects are also recognised.

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Appendices

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Appendix 1 External corrosion characteristics

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A1.1 Visual inspection and external corrosion appearance

A1.1.1 Visual Inspection

A detailed or close visual inspection (CVI) is generally the method used to locate areas of external corrosion, or scabs.

It is recommended that detailed photographic records are kept of the visual examination results. The availability of good photographic records is important to assist in the interpretation of any subsequent NDT results obtained. Some assessments can be made from a visual examination of the severity of the corrosion and its general characteristics.

A1.1.2 Typical corrosion stages

In the early stages of corrosion, a blister will form underneath the coating consisting of the corrosion product which forms over the corroded substrate. Examples of blisters with intact coatings are given in Figure A1-1.



Figure A1-1: Examples of early stage external corrosion which has formed blisters underneath the coating. Note the cracks in the coating in the upper left and lower examples.

As the corrosion progresses, and the corrosion product height increases, cracks can start to appear in the coating, as shown in the upper left and lower blister on Figure A1-1.

More extensive cracking in the coating and partial loss of the coating may then occur, as illustrated in Figure A1-2.



Figure A1-2: Example showing more extensive cracks in the coating and partial loss of the coating

At some point, the height of the external corrosion scab is sufficient to displace the coating which may then be lost, revealing the corrosion product itself, as illustrated in Figure A1-3. Once the corrosion product has been exposed it may then start to be lost (or spalled); it cannot be guaranteed that all the product remains in-situ.



Figure A1-3: Example of external corrosion showing loss of coating

The morphology of external corrosion can be highly variable, with some components having a relatively high density of separate and distinct corroded areas. Depending on the density and stage of the corrosion, these isolated scabs can start to merge.

Hence, as illustrated in Figure A1-4, in advanced cases of corrosion, the area affected can be generalised, and extended over a considerable area.



Figure A1-4: Example of widely distributed external corrosion with partial loss of coating

A1.2 Scab height to wall loss ratios

A1.2.1 Definitions and available datasets

One widely considered method for estimating the extent of the wall loss underneath a corrosion scab is to first measure the height, h , of the corrosion scab above the surrounding uncorroded surface of the component. To estimate the extent of the wall loss, w , the height, h , is divided by a factor, F , i.e.

$$W \sim h/F \tag{A1.1}$$

Note that in this definition, both the wall loss, w , and the scab height, h , are measured relative to the uncorroded surface (see Figure A1-5). Hence the maximum thickness of scab is given by the sum of h and w .

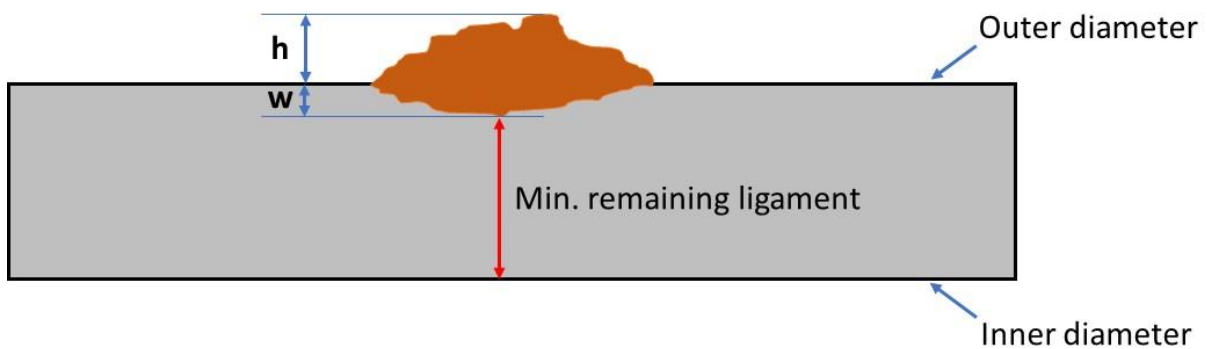


Figure A1-5: Diagram showing definition of scab height (h) and wall loss (w) values

Some data sets detailing the scab height to wall loss ratio for service-induced areas of corrosion were provided by current and previous HOIS members. Operator 1 originally provided measured scab heights and wall loss for two different categories of corrosion, namely ‘pitting’ and ‘general wall loss’. There was, however, limited information available with regards to the accuracy of these measurements, what components they originated from, the service history of the components and whether or not the scabs were original or had partially (or fully) spalled at any point during service life. Operator 2 supplied a much smaller data set containing five measurements from an oil export pipeline.

The reliability of the values in these historical datasets is unknown. For example, a few of the Operator 1 “general wall loss” values for F exceeded 20, with one being implausibly high at 80.

For the remaining three datasets (Operator 2 10” sch 20, Operator 1 6” sch 40 and Operator 1 6” sch 160), the benchmarking was performed by ESR Technology which resulted in greater confidence in the reliability of the measured scab height and wall loss values. To do this, ESR Technology accurately measured the heights of these natural corrosion scabs. These values were combined with careful measurements of wall loss, obtained either by precision internal UT scanning, or direct external measurements of wall loss, following removal of the corrosion product by blasting. These benchmarking methods then gave reliable measurements for the factor, F , as defined in equation (A1.1) above.

One significant complication with this approach can arise if some of the corrosion product has been lost from the corroded area, which can easily occur once the coating has been lost (see for example Figure A1-3). This was not however considered to be a major issue for the scabs benchmarked by ESR Technology.

A1.2.2 Values from available datasets

A compilation of all currently available data sets for scab height and wall loss is shown in Figure A1-6.

Table A1.1 provides the maximum and minimum scab height to wall loss ratios for the data sets, in addition to the best fit scab height to wall loss ratios, F . The level of scatter is indicated by the values given for the correlation coefficients, R^2 , and the root-mean-square (RMS) differences from the best fit straight lines (constrained to pass through the origin).

The correlation coefficient is one for perfect correlation and zero for no correlation. Hence an R^2 coefficient near to one would be indicative of a reliable method for estimating wall loss from a straightforward measurement of scab height. The available data shows substantial scatter in most, but not all, cases.

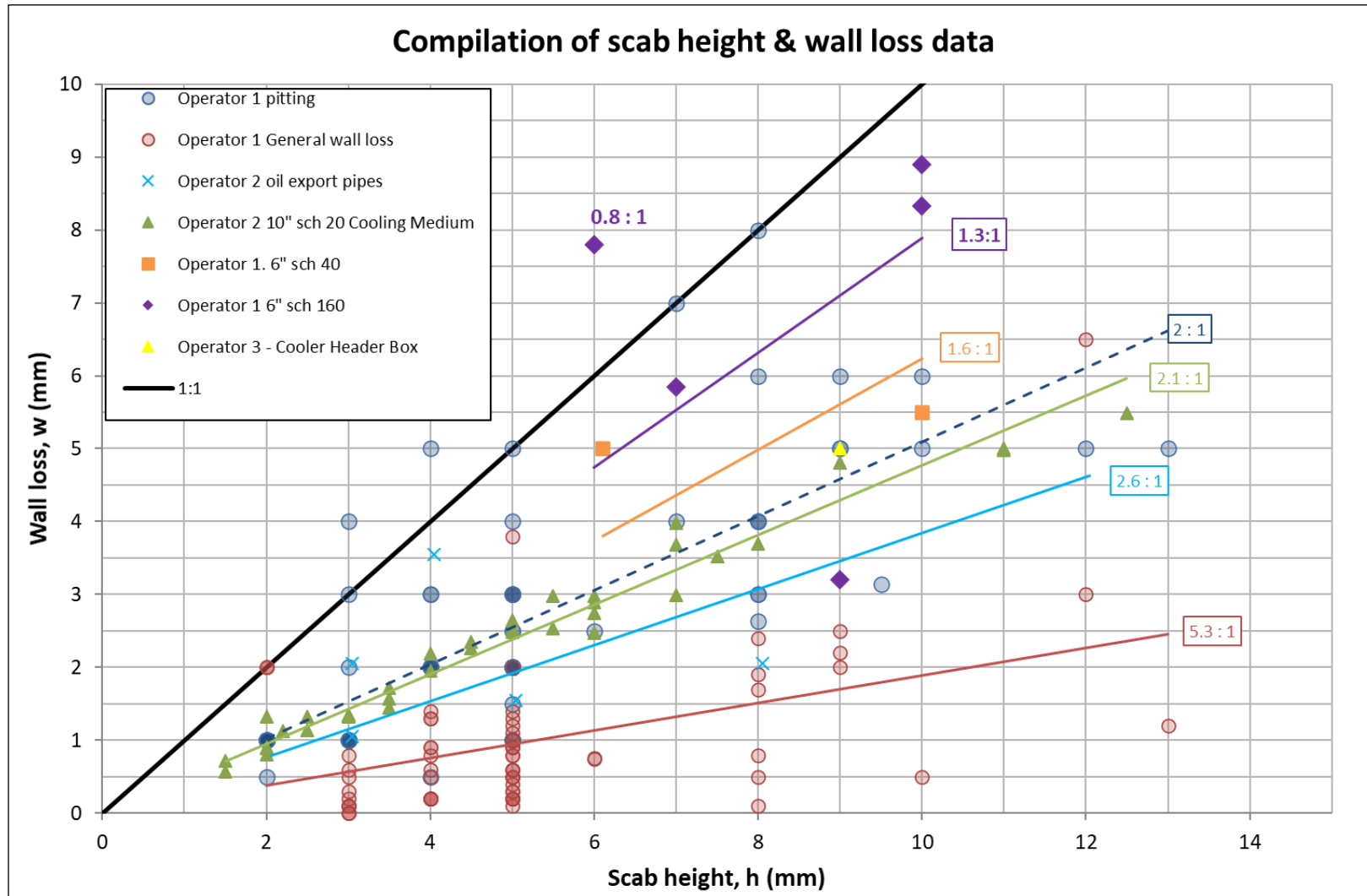


Figure A1-6: Graph showing scab height and wall loss data from all available sources

Table A1.1: Relationship between defect wall loss and scale height for available datasets

Data Set	Max. scab height to wall loss ratio (h/w)	Min. scab height to wall loss ratio (h/w)	Best fit scab height to wall loss ratio (h/w)	RMS difference from best fit (mm)	R² correlation coefficient
Operator 1: "pitting" ¹	8	0.8	2	2.0	0.58
Operator 1: "general wall loss" ¹	80	1	5.3	0.9	0.25
Operator 2: oil export pipe samples	4	1.1	2.6	1.1	N/A
Operator 2: 10" sch 20 Cooling Medium 30°C.	2.6	1.5	2.1	0.24	0.97
Operator 1: 6" sch 40 pipe samples (only 2 points)	1.8	1.2	1.6		N/A
Operator 1: 6" sch 160 thick walled pipe samples	2.8	0.8	1.3	2.3	N/A
Operator 3 (only 1 point)	1.8	1.8	1.8	N/A	N/A

Footnote:

¹ Historical data with limited information on origin and reliability

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The dataset showing the least scatter was that of 10" sch 20 pipes obtained and benchmarked by HOIS from Operator 2. The pipework formed part of the Cooling Medium system which had a low operating pressure of at most approx. 10bar, and operating at about 30°C. It was on the extremities of an offshore platform and the top section where the scabs formed were not visible from walkways. The scabs formed apparently from drips of water from a structural beam above it. For these scabs, the best fit scab height to wall loss factor F was 2.1 with a small (0.24mm) root-mean-square difference from the best fit. Hence for these scabs, measurement of the scab height, followed by division by 2.1, gave an accurate estimate of the wall loss.

It was found in the recent HOIS C19-01 project that of the HOIS members that estimated the wall loss by measuring the scab height, the ratios used ranged from 2.5:1 to 10:1. There are other anecdotal accounts of factors that are found to work well for other components experiencing common corrosion conditions, but additional well documented, published data on these factors has not been found. Appeals to HOIS members and to non-HOIS members (via LinkedIn) resulted in additional data from one HOIS member.

However, based on general feedback from industry, it appears that a predictable relationship between scab height and wall loss is the exception rather than the rule, as evidenced by the much larger scatter shown by the other datasets included in Table A1.1 and Figure A1-6. For example, the dataset for the Operator 1 6" sch 160 pipes showed factors, F , that ranged from 0.8 to 2.8 (ESR benchmarking).

The minimum scab height to wall loss ratio within the available datasets was 0.8 (within the Operator 1 pitting data and Operator 1 6" sch 160 thick walled pipe samples).

A1.2.3 Summary

There is widespread interest in the potential applicability of measurements of scab height as a basis for estimation of wall loss, as this is a relatively straightforward, fast, and low-cost method. If reliable estimates could be obtained in this way, there would be no need to consider further application of the NDT methods described elsewhere in this document (Appendix 2).

However, it is also widely perceived that the method is inherently unreliable, and it is unclear what factor to use when converting from scab height to wall loss.

An additional major complication is that some of the corrosion product may have been lost if the original coating is no longer present.

Under certain conditions, it appears that corrosion with a consistent scab height to wall loss ratio can be obtained, over a wide range of corrosion severities (e.g. the factor, F , of 2.1 found for the 10" sch 20 pipes provided to HOIS by Operator 2) – see Figure A1-6 and Table A1.1.

On the basis of available information, it is however unclear how the factor F is influenced by the corrosion conditions, and hence it is not possible to predict what an appropriate value would be for a particular corroded area.

The available scab height and wall loss data does however suggest that a mostly conservative "rule of thumb" value to use would be $F = 1$, i.e. the wall loss, w , is equal to the scab height, h (see Figure A1-5 for definition of these values), i.e. considering a 1:1 ratio. It should be recognised that the data set on which this is based is limited and is thought to be primarily based on results from offshore, North Sea operations. Hence the 1:1 ratio can not be taken as universally conservative and should only be considered, as appropriate, as a basis for estimates where the resulting wall loss is not approaching an integrity limit and there is also

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good evidence that corrosion product has not been lost from the scab (i.e. the corroded area is still effectively a 'blister' under the coating – see the examples shown in Figure A1-1).

A1.3 Examples of external corrosion morphologies

A1.3.1 Methodology

Two different sets of ex-service pipes with external corrosion scabs were available for benchmarking by ESR Technology.

Information was gained on the morphology of the areas of wall loss in these pipes using internal ultrasonic scanners, followed by processing of the resulting 0° pulse-echo data using methods in full accordance with the HOIS RP on precision thickness measurements [3].

Although the quality of the data was somewhat degraded by the internal surface condition of the pipes, the resulting maps of remaining thickness gave, for each area, values for the maximum wall loss, and the extents of the corroded areas in the axial and circumferential directions. The remaining thickness maps also provided information on the morphology of the wall loss, including the presence of any localised pits, within the corroded areas.

To characterise the morphology, the following measures of aspect ratio and volume fill factor were used.

A schematic of an area of wall loss showing its average extent E (average of its axial and circumferential extents) and its maximum wall loss, w , is given Figure A1-7.

The aspect ratio, A , of this area is defined by:

$$A = E/w \quad (A1.2)$$

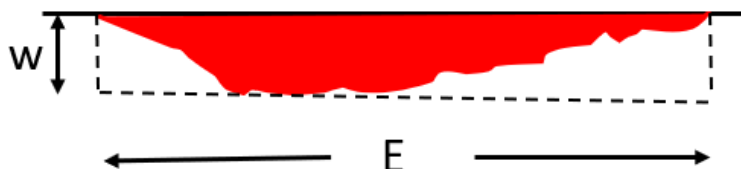


Figure A1-7: Schematic of an area of wall loss showing its average extent E and its maximum wall loss (w)

Another relevant parameter is the fraction of volume occupied by the wall loss, compared with that of a flat-bottomed hole having the same maximum wall loss, w , and diameter, E .

This volume fill factor, f , is calculated from:

$$f = V / (0.25 \pi w E^2) \quad (A1.3)$$

where,

V is the volume of the area of wall loss.

To find estimates of the volumes of the corroded areas, 3-D CAD models were generated for some of the areas. This then allowed a standard CAD function to be used to find the volume

of the corresponding 3-D model. This then allowed the volume fill factors to be found for all the areas for which CAD models were generated.

A1.3.2 10" sch 20 pipes

A set of four 10" sch 20 ex-service pipes were obtained and benchmarked by ESR Technology. The pipework formed part of the Cooling Medium system which had a low operating pressure of at most approx. 10bar, and operating at about 30°C. It was on the extremities of an offshore platform and the top section where the scabs formed were not visible from walkways. The scabs apparently formed from drips of water from a structural beam above it.

The severity of these scabs varied widely with some having only a fraction of a millimetre of wall loss, whereas others were much more severe, and almost through-wall in places.

Examples of the ultrasonic thickness maps obtained from these pipes using an internal UT scanner are given in Figure A1-8, Figure A1-9 and Figure A1-10.

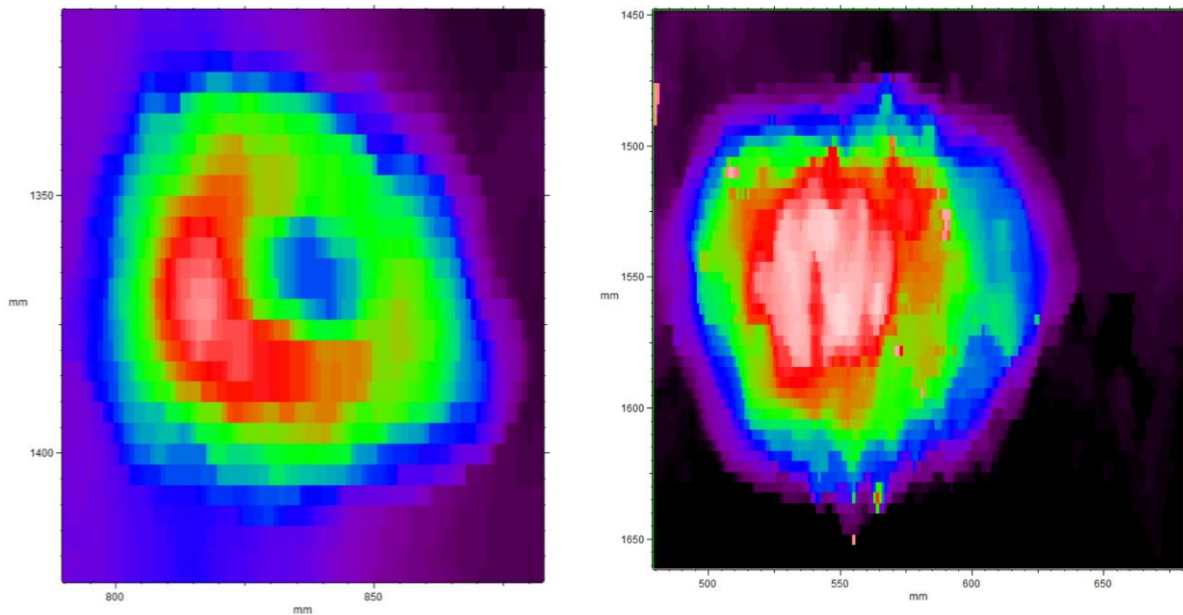


Figure A1-8: Examples of ultrasonic C-scans showing remaining thickness of two scabs on the 10" sch 20 pipes (as a function of circumferential and axial directions) with the axial direction being shown vertically

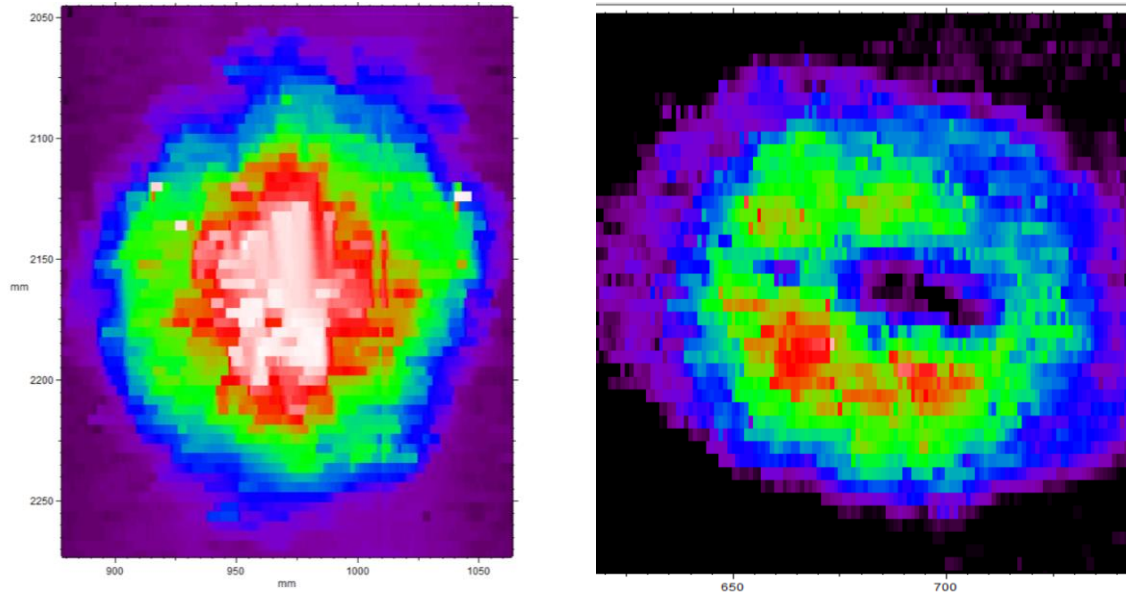


Figure A1-9: Further examples of ultrasonic C-scans showing remaining thickness of two scabs on the 10" sch 20 pipes (as a function of circumferential and axial directions) with the axial direction being shown vertically

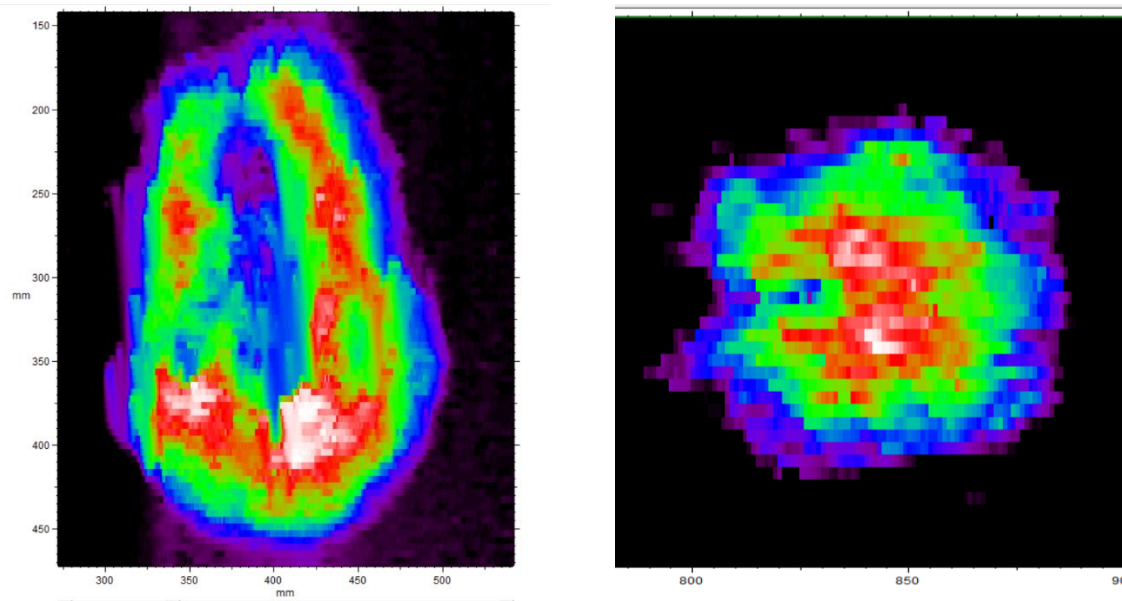


Figure A1-10: Further examples of ultrasonic C-scans showing remaining thickness of two scabs on the 10" sch 20 pipes (as a function of circumferential and axial directions) with the axial direction being shown vertically

From the above figures, it is apparent that the morphology of the wall loss in these areas is generally complex and variable with considerable structure and, in some cases, fine detail within the corroded areas.

Some areas (e.g. Figure A1-9 left) show a reasonably simple, single peaked area of wall loss with the wall loss tapering off from the centre of the area outwards. In contrast, other areas

show different patterns of wall loss, including those with annular characteristics (e.g. Figure A1-8 left, Figure A1-9 right and especially Figure A1-10 left).

A typical length scale of the variations in wall loss is difficult to determine for these corroded areas, although in most cases the wall loss features are typically a few tens of millimetres across.

Figure A1-11 shows the maximum wall losses of the corroded areas as a function of their average circumferential and axial extents. The best fit straight-line to this scatter plot has a gradient of 37. Note the apparent increase in scatter for wall losses greater than 5mm.

The average aspect ratio of the areas was ~40. The aspect ratios of individual areas however varied substantially, with a minimum of ~20 and a maximum of ~70.

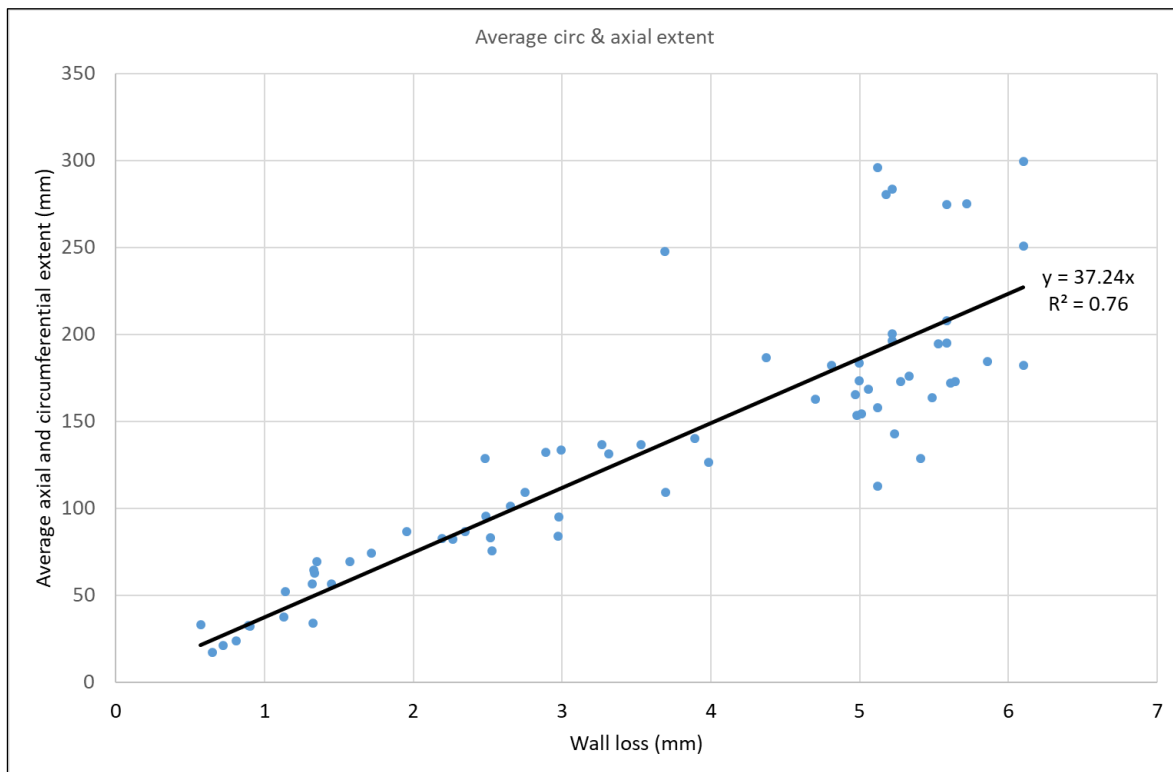


Figure A1-11: Maximum wall losses of the ex-service corroded areas as a function of their average circumferential and axial extents

Using a methodology involving the construction of 3-D CAD models for a selection of the areas in these pipes, it was found that on average the volume fill factor was ~0.35, i.e. the volume of the wall loss was only about one third of a flat-bottomed hole of the same maximum wall loss and extent. Some of the areas had appreciably lower fill factors.

A1.3.3 6" sch 160 pipes

Five ex-service samples were kindly provided by a cat 1 HOIS member. These were 6" sch 160 pipes (18.3mm nominal wall) and had extensive external corrosion. The corrosion varied from surface corrosion due to coating breakdown, through localised scabs to large areas of heavy scab formation.

There were relatively large areas both of slight corrosion and also heavy corrosion. In addition, there were some smaller areas of more localised corrosion/scabs with surrounding areas with fair/reasonable surface condition for external UT.

Figure A1-12 shows one of the corrosion scabs on these ex-service pipes and the corresponding UT C-scan. Note the close correspondence between the visual extent/shape of the scab and the UT C-scan.

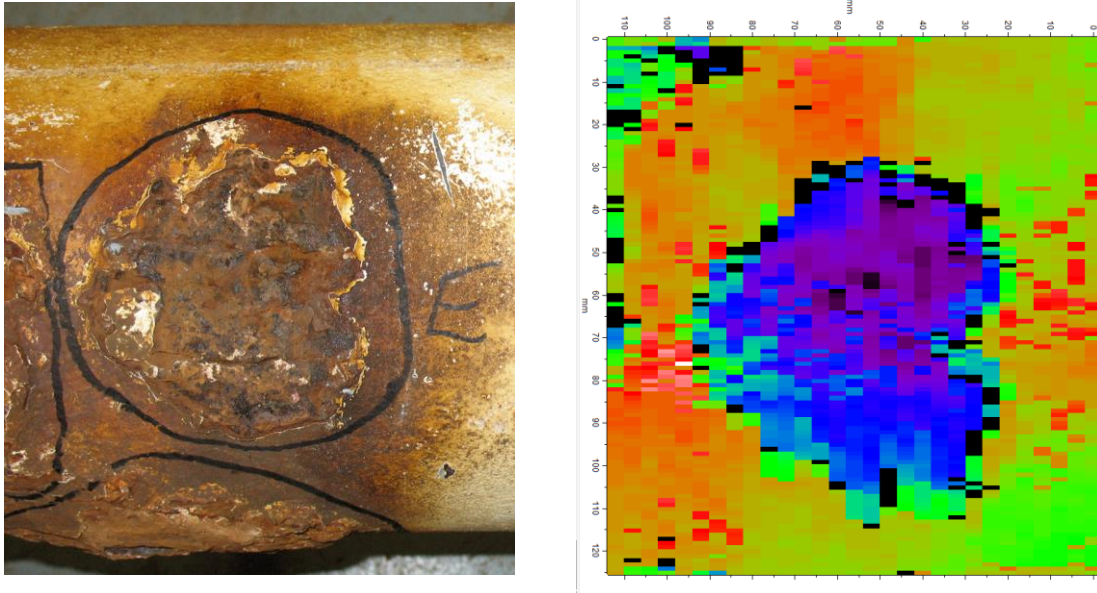


Figure A1-12: Photo of moderate ex-service scab (left) and corresponding UT remaining thickness map/C-scan (right) obtained with the ESR 'piglet' internal scanner

A larger scab and the UT C-scan obtained from it is shown in Figure A1-13. Note that on the C-scan, some of the areas of wall loss appear to be quite localised.

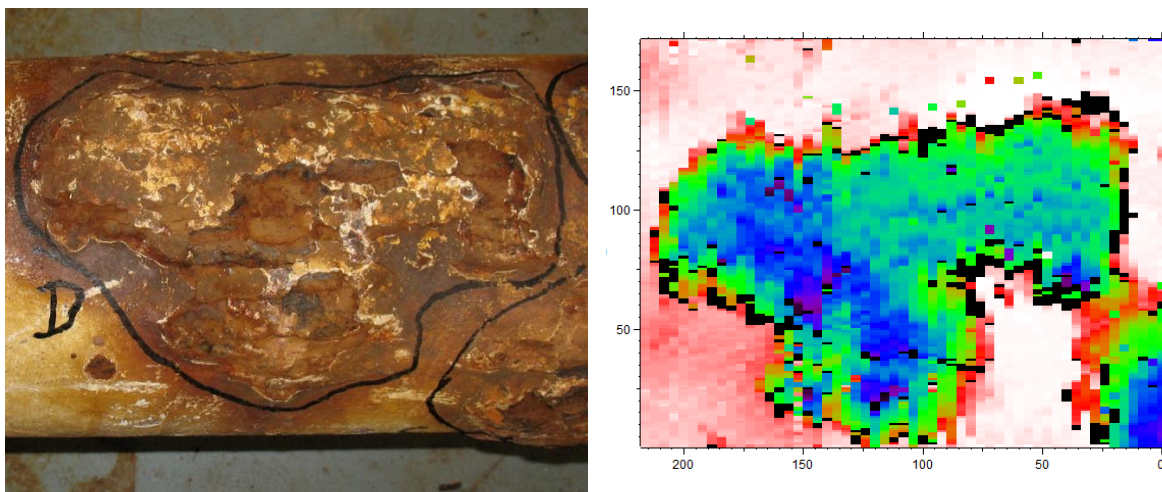


Figure A1-13: Photo of a larger ex-service scab (left) and the corresponding UT remaining thickness map/C-scan (right) obtained with the ESR 'piglet' internal scanner

A further example of another larger scab and the UT C-scan obtained from it is shown in Figure A1-14. In this case, there are several localised features, or pits, superimposed on large areas of near uniform wall loss.

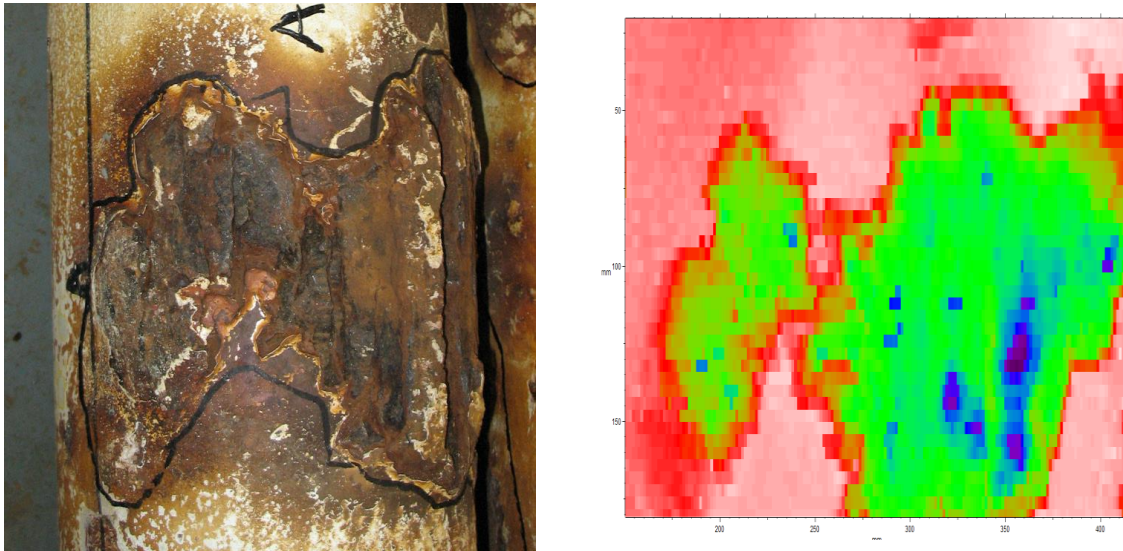


Figure A1-14: Photo of a larger ex-service scab (left) and the corresponding UT remaining thickness map/C-scan (right) obtained with the ESR 'piglet' internal scanner, showing pronounced localised features.

One of the ultrasonic B-scans from the above scan (Figure A1-15) shows the pronounced nature of the localised pitting in this scab which in this case corresponds to an additional wall loss of ~ 5mm over a total circumferential extent of ~ 15mm.

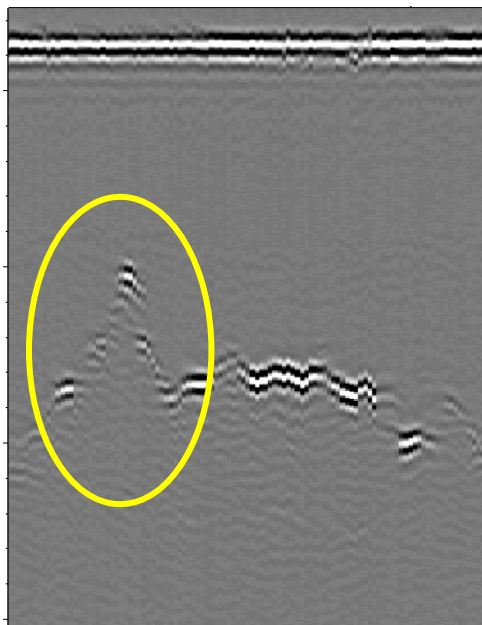


Figure A1-15: B-scan of data showing pronounced localised pitting along one circumferential scan line

A further example is provided by the smaller scab shown in Figure A1-16 which is still covered by coating. The C-scan shows an area of large-scale loss of wall coincident with overall extents of the scab, again superimposed on this there are some highly localised areas of additional wall loss. These are up to ~3 mm deeper than the surrounding surface and only about 5mm x 5mm in axial/circumferential extent.

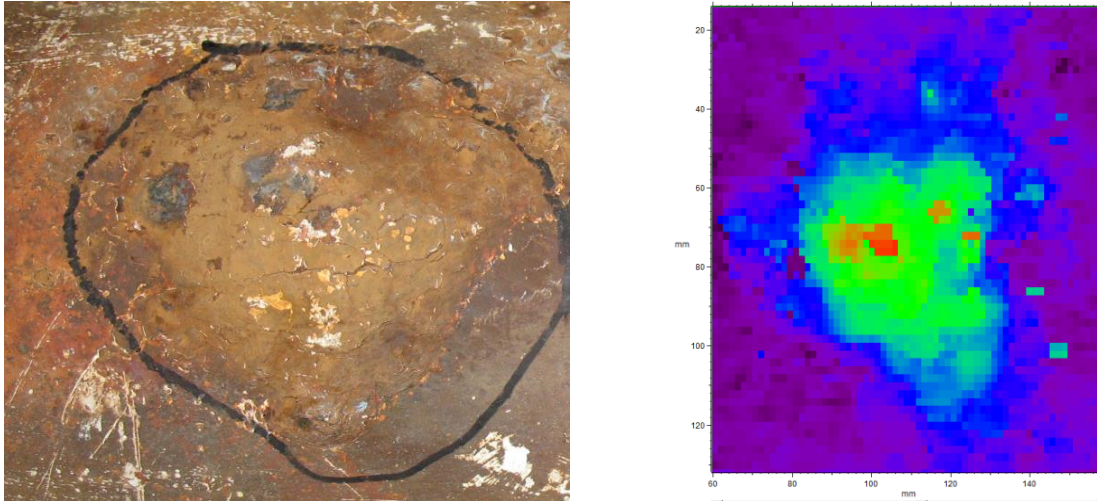


Figure A1-16: Photo of a smaller ex-service scab still covered by coating (left) and the corresponding UT remaining thickness map/C-scan (right) obtained with the ESR 'piglet' internal scanner showing pronounced localised features

Figure A1-18 shows an extensive corrosion scab affecting the full pipe circumference with an axial length > 1m. The corresponding C-scan shows an extensive area of near uniform wall loss, with two highly localised pits superimposed in different, apparently random locations. C-scans are also shown from two detailed scans, made at full resolution. These show that the deeper pit has an additional wall loss of ~4mm over an area of about 8mm (axial) x 6mm (circ.).

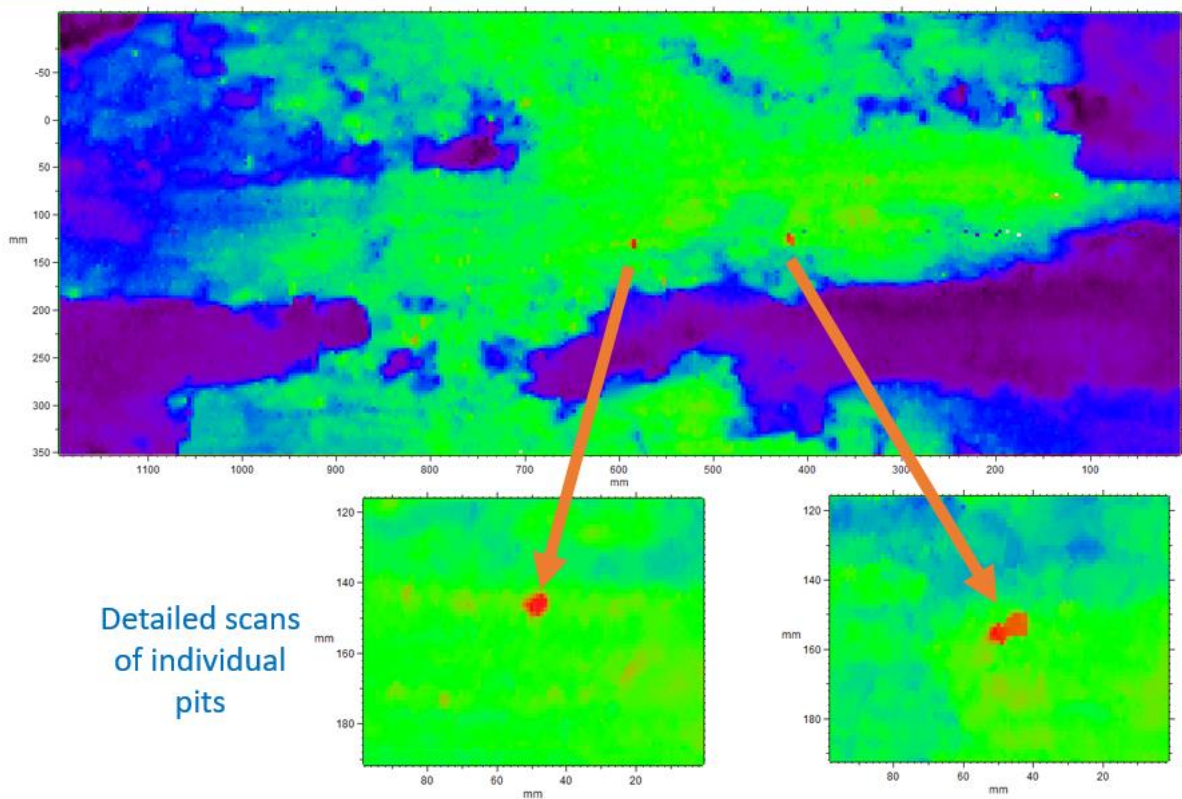


Figure A1-17: Photo of an extensive area of corrosion (top) and the corresponding UT C-scan (below). Two detailed C-scans of individual pits are also shown.

A1.3.4 Summary

The internal UT scans on the 6" sch 160 pipes, performed using the ESR Technology designed and manufactured 'piglet', have shown that several of the areas of corrosion have morphologies that significantly differ from those of the 10" sch 20 ex-service examples of external corrosion scabs examined previously.

The morphologies of some of the corroded areas on the 6" sch 160 pipes include a number of examples of areas of highly localised, and often isolated pits, superimposed on generalised

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wall loss. These localised pits have significant additional wall losses of ~3-5mm compared with the surrounding corrosion, over circumferential/axial extents of ~5-15mm.

In comparison, those scabs in the 10" sch 20 pipes lacked these highly localised pits and had irregularities in wall loss over significantly larger length scales (typically a few tens of millimetres, although this varied from one scab to another).

A summary of the aspect ratios of the scabs benchmarked on these two sets of pipes is shown in Table A1.2. For the 10" sch 20 pipes, the mean volume fill factor, f is also given.

Table A1.2: Summary of scab aspect ratios and volume fill factors for available ex-service pipes

	Ex-service pipes	
	10" sch 20	6" sch 160
Mean aspect ratio, A	40	30
Max aspect ratio	70	65
Min aspect ratio	20	10
Mean volume fill factor, f	~0.35	

A1.4 Photogrammetry and Laser Scanning

An approach investigated in the recent C19-01 HOIS project was the use of photogrammetry and/or laser scanning to produce a 3-D model of the external profile of the scab being assessed [6]. This would provide information to assist the interpretation of double wall radiographs (see Appendix A2.5.5) obtained to screen for the presence of localised corrosion pitting within the scab, which if present, would reduce the accuracy of other NDT methods intended to provide sizing information on remaining ligament.

Radiographic indications might be due to localised corrosion pits or irregularities in external scab profile. Hence knowledge of any irregularities in the external profile of the scab, caused for example by partial spallation of scab material could be used in the interpretation of any indications present on the radiograph and help identify any likely to be due to localised pitting corrosion.

A limited trial of photogrammetry, as a low cost alternative to 3-D laser scanning, was conducted. For this, external corrosion scabs were photographed at multiple angles using a 12 MP iPhone to assess the effectiveness of a relatively low cost, but convenient, camera phone. A 3-D model was then subsequently generated using commercially available photogrammetry software. The 3-D model could then be manipulated to provide a better understanding of the scab morphology and is a considerable improvement on using 2-D images. Still images taken from a 3-D model of an external corrosion scab are shown in Figure A1-18.

The potential for extracting measurement data from the 3-D models was then investigated by analysing the point cloud data, exported in the Stereolithography (STL) file format. This was done using code written by ESR in the Julia programming language for fitting a cylinder as a reference surface and then producing a 2-D height map. The resulting 2-D height map is shown in Figure A1-19, with the areas in white signifying the highest points of the scab, followed by red, green, blue, and finally purple. It must be noted that apart from using the nominal OD of the pipe, no other calibration method was used for this initial attempt.

For an example of the application of this method to improving the interpretation of double wall radiographs, see Appendix A2.5.5.2.

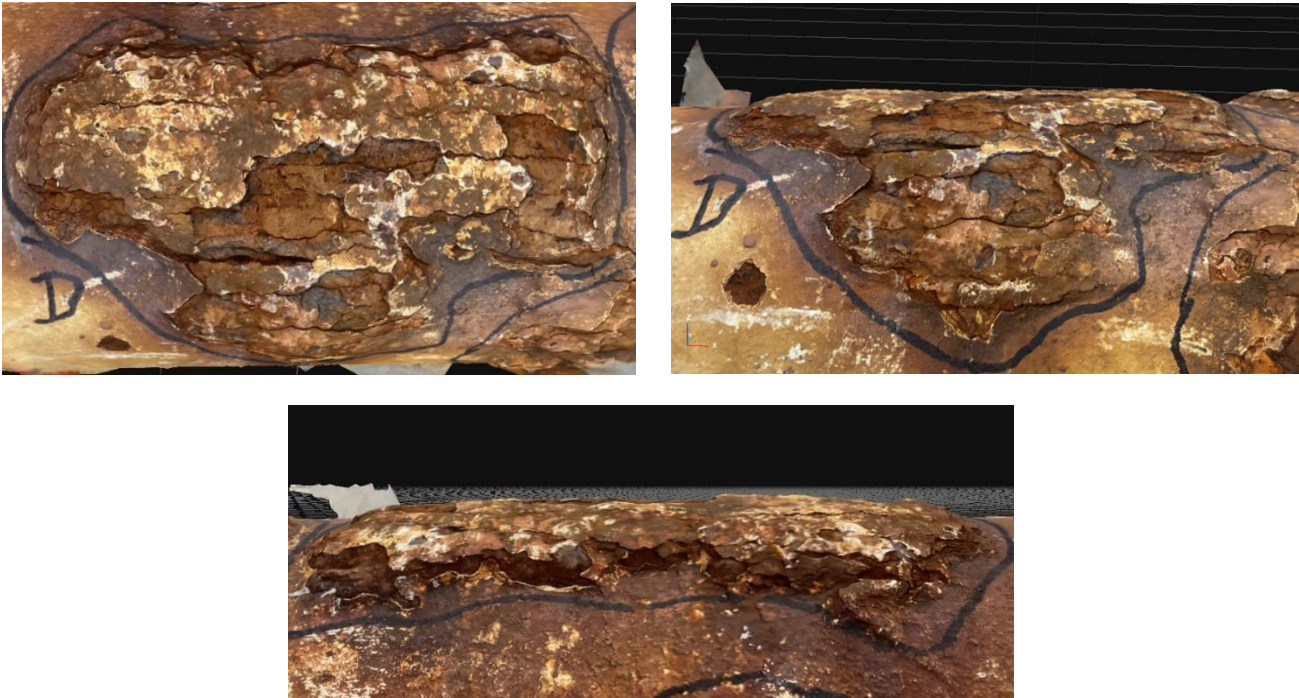


Figure A1-18: Images of a 3-D model of an external corrosion scab using photogrammetry

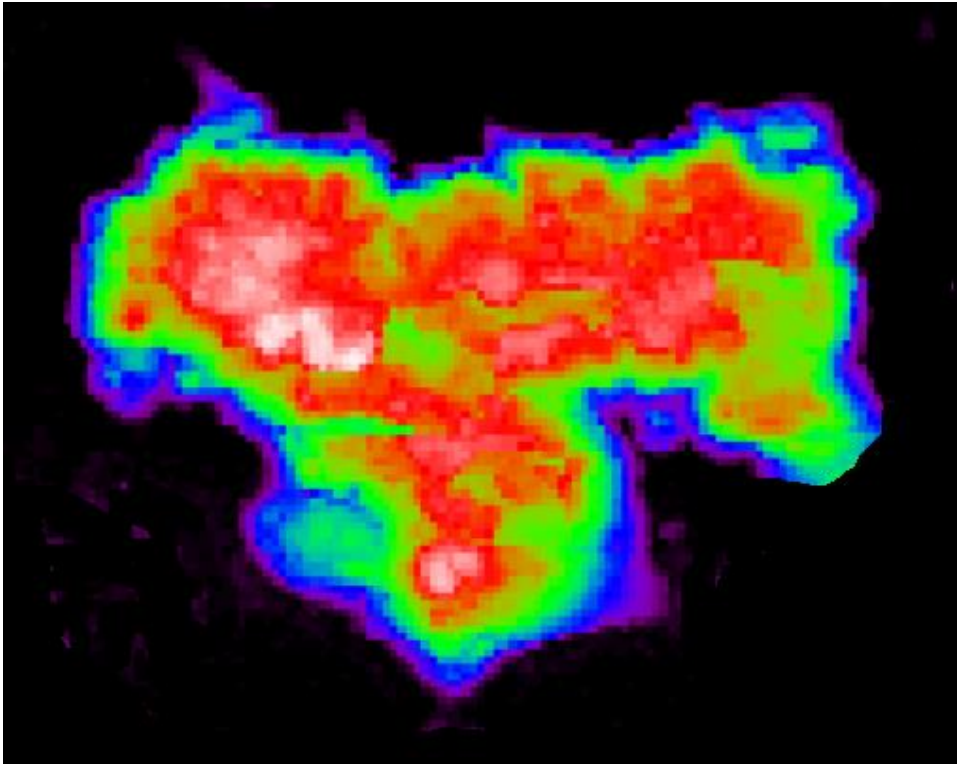


Figure A1-19: 2-D height map of scab shown in Figure A1-18

To determine the accuracy of measurements derived from photogrammetry, pipe samples containing CNC-machined areas of wall loss that had been fully benchmarked, were assessed using both photogrammetry and Creaform laser scan data, and the results compared. The deepest points on a limited number of samples showed reasonable correlation with a maximum difference of 0.3 mm between the two techniques. An example of the 2-D depth maps created using both techniques is shown in Figure A1-20. Whilst the map obtained from photogrammetry displayed a lower spatial resolution, the general features were consistent with the Creaform scan.

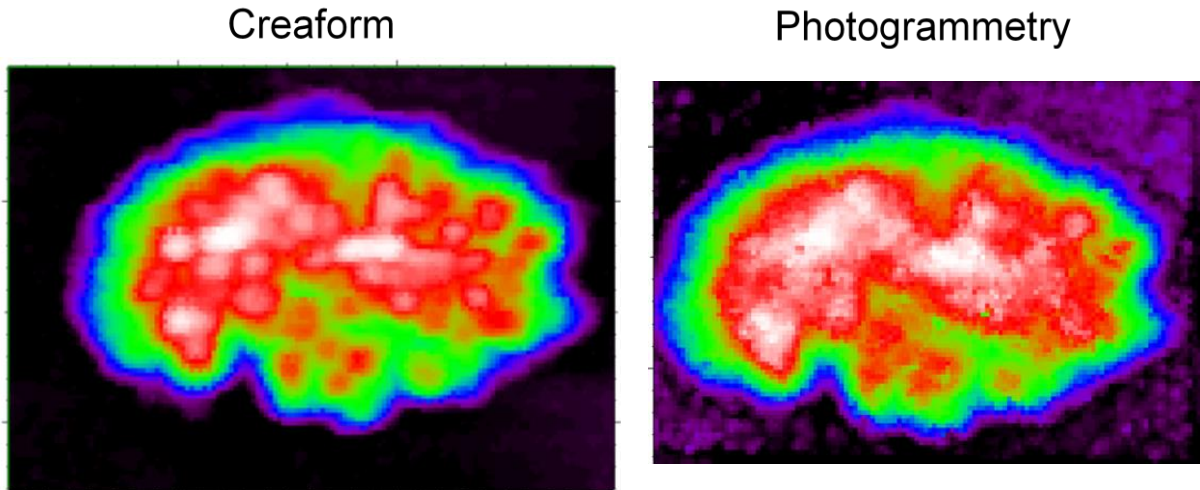


Figure A1-20: Comparison of 2-D depth maps produced by Creaform and photogrammetry

Appendix 2 NDT methods

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A2.1 Pulsed eddy currents

A2.1.1 Introduction

For NDT of scabs, the pulsed eddy current (PEC) sensor is positioned above the scab, with the aim of measuring the remaining wall thickness within the sensor footprint, directly beneath the sensor, as illustrated in Figure A2-1.

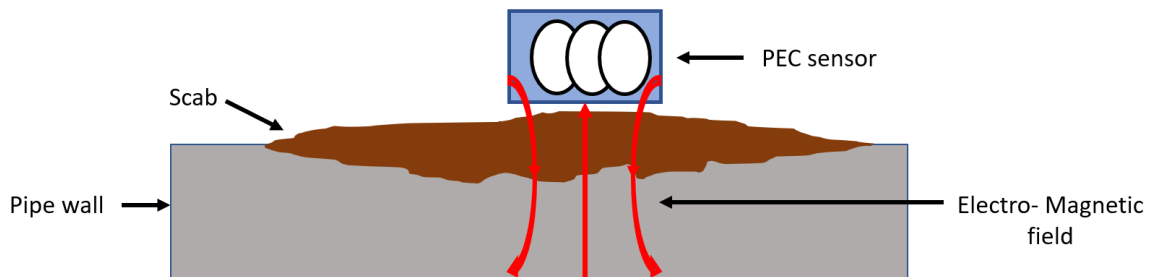


Figure A2-1: Principle of the pulsed eddy current method for measurement of the remaining wall thickness under a scab

This technology was originally developed for CUI inspection in the 1990s and two similar systems were available, one developed by Shell (PEC) and the Applus RTD Incotest unit.

With the expiry of the original patents associated with pulsed eddy currents, additional equipment manufacturers are now offering PEC systems. The main current providers include:

- Eddyfi – Lyft
- TUV Sonovation – Sonopec
- Maxwell NDT - PECT

The Eddyfi Lyft system is based on the same general physical principles but has the important capability of being able to continuously scan a component. In addition, an array of PEC sensors is now available from Eddyfi (PECA).

The original Shell PEC technology has now been adopted by TUV Sonovation, and updated software has been developed. It is understood that improved probes are currently under development.

Maxwell NDT is also offering an updated PEC system, with different electronics and probes.

A2.1.2 Overview of method

The pulsed eddy current (PEC) method involves measurements of the decay of the eddy currents induced in the object under examination. A steady state eddy current is induced in the material by means of a direct current circulating through the sending coil circuitry of the sensor. This direct current generates a magnetic field that needs some time to become uniform and stable. The magnetic field lines generated are closed lines and move through the insulation and the ferromagnetic object under examination.

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When the current is cut off the magnetic field decays. During this transient, eddy currents are induced in the ferromagnetic object under examination. These eddy currents migrate through the object wall and rapidly decay when they reach the opposite side of the object.

During decay, the eddy currents generate a variable magnetic field. Field lines move through the sensor receiving coils inducing a current. The system measures the resulting voltage across the coil which is a function of time depending on the object thickness and on the material electromagnetic properties.

The measured signal is usually shown on a plot in which the horizontal axis represents the logarithm of the time in milliseconds and the vertical axis the logarithm of the measured signal amplitude (see Figure A2-2). A particular characteristic of this signal is the presence of a bending point that indicates the induced Eddy Current decay time. At this time, the Eddy Current has reached the backwall and rapidly disappears (signal drop after the bending point). This bend point time, τ , is a function of the material magnetic permeability (μ), of the material electrical conductivity (σ) and of the square of the object average thickness in the footprint area (d):

$$\tau = \mu\sigma d^2. \tag{A2.1}$$

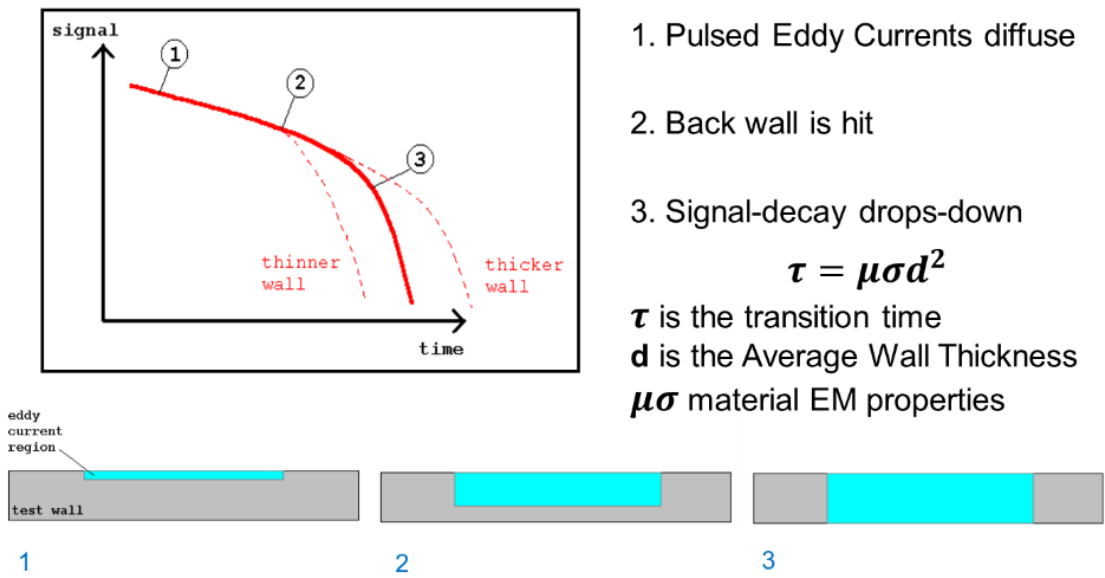


Figure A2-2: Pulsed eddy current signal plotted as a function of time for different remaining wall thicknesses (courtesy TUV Sonovation)

Calibration methods are used to find the unknown variables in this equation ($\mu\sigma$), allowing a relative measurement of the object average thickness within the sensor footprint to be found from the bend point time, τ . Alternative analysis methods can also be used to measure the relative wall thickness local to the probe.

Note that the method will detect both external and internal wall loss if it is present, without discriminating between near side and far side defects.

An example of equipment for pulsed eddy current inspection of scab is shown in Figure A2-3.



Figure A2-3: Eddyfi Lyft equipment for pulsed-eddy current inspection of an external corrosion scab (courtesy of Eddyfi)

A notable recent development has been the introduction of PEC arrays which comprise multiple PEC sensors arranged side by side. When the sensors can be operated simultaneously, instead of sequentially, significantly improved coverage rates can be achieved compared with single PEC probe systems.

A2.1.3 Application to external corrosion inspection

Although PEC equipment is often used for inspection of corrosion under insulation (CUI), it can also be applied to measurement of the remaining wall thickness under an un-insulated corrosion scab.

At any one point, the sensor provides a measurement of remaining wall thickness, averaged over the sensor footprint area. Hence the method is most effective for large scale wall loss, which is near to uniform over the sensor footprint area. More localised wall loss can be detected, but with reduced sensitivity.

Sensor footprint averaging is an effect whereby localised pitting can be undersized by PEC, depending upon the area of the sensor footprint compared with that of the pitting corrosion. For this reason, smaller PEC probes, which have a reduced sensor footprint size are preferred for inspection of uninsulated corrosion scabs, where possible. However, for thicker-walled pipes, these sensors may give inadequate sensitivity resulting in the need to use a larger probe.

For example, the Eddyfi small single PEC probe (PEC-025-G2) has a sensor footprint size quoted as being ~43mm for a 13mm lift-off. The new Eddyfi array probe for scabs (PECA-HR-SM) has a somewhat smaller quoted footprint size of 30mm (for a 13mm lift-off). Both are specified as being applicable to wall thicknesses up to about 20mm. For larger wall thicknesses, larger sensor sizes are needed with sensor footprints of ~ 65mm.

For a scab, it is advisable to scan the PEC probe over the corroded area, as the minimum remaining wall thickness may not correspond to the centre of the area, nor the highest point on the scab. Gridded measurements are often taken using PEC, but some equipment can be continuously scanned, providing a greater measurement density.

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The time taken for a point measurement varies depending on the wall thickness (assuming constant electromagnetic properties), but the sensor can be scanned (in a stop/start manner) to provide a set of point measurements which can then be assembled into colour thickness maps.

The corrosion product material, which may have varying levels of magnetic properties, may affect the PEC sensor readings, potentially giving a reduced loss of wall thickness measurement. However, in HOIS trials, this effect has been shown to be small, provided there is a small offset between the PEC sensor and the scab [1].

In an attempt to mitigate the effects of sensor footprint averaging, some PEC systems have software that provides differing algorithms to derive the remaining wall thickness at each scan position. The standard methods used for PEC data provide values that are averaged over the sensor footprint and are referred to as AWT.

Alternative algorithms are available from some manufacturers, which provide values that are said to be compensated for the sensor footprint averaging effect (e.g. CWT values from Eddyfi) and “defect” wall thickness (DWT) values from TUV Sonovation.

In some of the HOIS trials, these CWT or DWT values gave improved accuracy for measurement of the remaining wall thickness for some of the corroded areas scanned, compared with the AWT values for the same areas.

An example of a PEC C-scan map of an externally corroded area, without insulation, on a 10” Sch. 20 (6.4mm nominal wall thickness) pipe is given below in Figure A2-4.

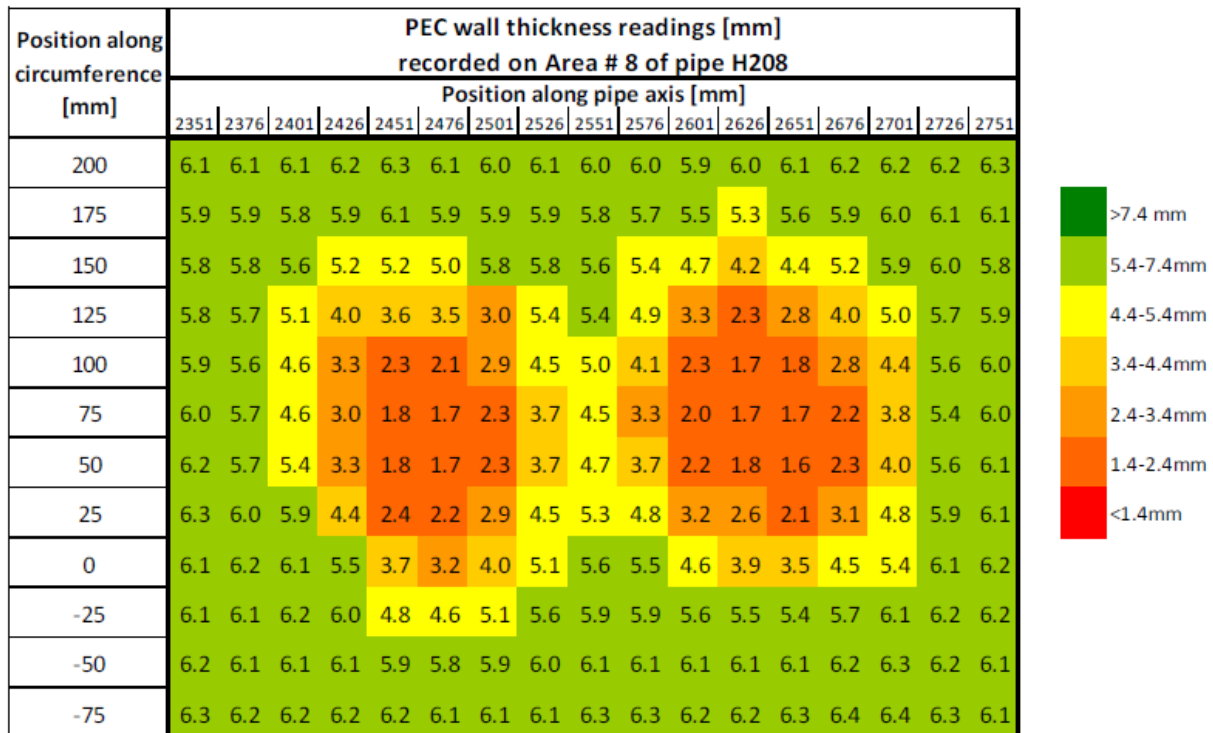


Figure A2-4: An example of a thickness map (C-scan) of an external corrosion scab (courtesy of Bilfinger and Shell Global Solutions International)

A2.1.4 HOIS trials

There have been significant developments in PEC technology over the last few years. A new version of the Lyft system (Lyft 2.24), with a small sensor designed for application to externally corroded components was available from August 2021. The reduced sensor size is intended to reduce the sensor footprint averaging effect, and this combined with the use of the CWT, may lead to improved measurement accuracy, depending on the corrosion morphology. The highly localised pitting found in some of the HOIS ex-service pipes (see Appendix A1.3), may still present challenges for this technology.

The most recent HOIS trial (C19-01) of PEC for scab inspection was a blind trial conducted in late 2020 on two pipes (10" NB / Sch.60) exhibiting areas of CNC-machined wall loss based on corrosion from ex-service pipes [5]. As the main focus of this project was to assess the effectiveness of NDT techniques in determining the minimum remaining ligament of scabs containing localised pitting, both pipes exhibited varying degrees of localised pitting in an otherwise more general wall loss. A mixture of modelling clay and crushed magnetite, which is ferrimagnetic, was applied to each area of wall loss to simulate scab material.

Assessment of the pipes with the Eddyfi Lyft system and the new PECA-HR array probe (with CWT) resulted in significant undersizing, with a maximum undersizing of 33.3%, a maximum oversizing of 18.1% and an average of 7.5% for the first pipe, and a maximum undersizing of 28.2%, a maximum oversizing of 11.8% and an average of 14.8% for the second pipe. Interestingly, when the deepest isolated pits were omitted from the second pipe (by altering the benchmark values to reflect the remaining wall thickness excluding the additional localised pits), the maximum undersizing, maximum oversizing, and average values were 14.3%, 22.5%, and 4.8%, respectively. This therefore suggests that the isolated machined pits for this pipe were not detected.

In the same trial, the Maxwell PECT unit which uses AWT achieved a maximum undersizing of 36.9%, a maximum oversizing of 10.9%, and an average of 25.7% for the first pipe, and a maximum undersizing of 37.4%, a maximum oversizing of 21.4%, and an average of 30.9% for the second pipe. Again, the three values were lower (27.9% maximum undersizing, 15.8% maximum oversizing, and 20.8% average) when the isolated pips were omitted. This again suggests that the isolated machined pits for this pipe were not detected.

Earlier HOIS PEC trials were hosted in 2013 & 2014 on a set of ex-service thin-walled pipes (10" sch 20). These trials were of the original Shell PEC system and the ApplusRTD Incotest equipment. The reported AWT values from both trials also showed significant undersizing due to sensor footprint averaging effects (by ~20% WT). Measurements obtained with the ApplusRTD DWT algorithm showed less undersizing (~8% WT), but this was based on a limited number of corroded areas [1].

A2.1.5 Summary

Method:	Pulsed eddy current method for determining remaining thickness under external corrosion scabs (un-insulated)
Basis:	PEC method provides measurements of remaining wall thickness under the probe, through the corrosion product.
Strengths:	<ul style="list-style-type: none"> • Single sided so can be applied to vessels and pipes • Faster continuous scanning with some equipment • Array probes for significantly higher coverage rates with some equipment • Advanced data analysis algorithms are now available from some suppliers that seek to compensate for sensor footprint averaging effects. Trials have shown that the resulting measurements (CWT, DWT) then agree better with the benchmark values for remaining wall thickness than the conventional AWT measurements.
Limitations:	<ul style="list-style-type: none"> • Averages over sensor footprint area, so can undersize localised areas of corrosion. • Affected by local changes of geometry (e.g. tees), although can be applied to some elbows. • The conventional measurements of remaining wall thickness averaged over the sensor footprint (AWT) can significantly underestimate the extent of the wall loss under a scab, depending on the degree of localisation of the corrosion.
Overall:	Best suited to extended areas of corrosion lacking localised pitting or other fine structure within the wall loss morphology. Thinner-walled pipes (< 20mm) allow use of the preferred smaller footprint PEC probes. For more information, refer to manufacturer's documentation.

A2.2 Dual frequency and phase shift eddy currents

A2.2.1 Introduction

Eddy current testing is based on the phenomenon of electromagnetic induction. In an eddy current probe, an alternating current flows through a wire coil and generates an oscillating magnetic field. If the probe and its magnetic field are brought close to a conductive material like a metal test piece, a circular flow of eddy currents will begin to move through the metal. The eddy currents flowing through the metal will in turn generate a magnetic field, which will interact with the coil and its field through mutual inductance (see Figure A2-5).

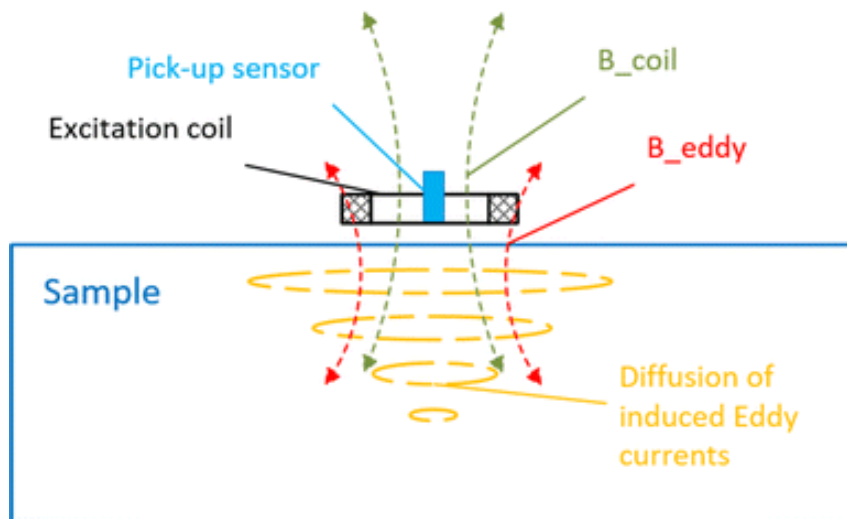


Figure A2-5: Principle of the eddy current method for NDT

Eddy current testing is normally used to detect defects like near-surface cracking which will interrupt or alter the amplitude and pattern of the eddy current and the resulting magnetic field. This in turn affects the movement of electrons in the coil by varying the electrical impedance of the coil. The eddy current instrument plots changes in the impedance amplitude and phase angle, which can be used by a trained operator to identify changes in the test piece.

A2.2.2 Application to external corrosion inspection

For scabs, the eddy current method is used to determine the lift-off between the eddy current probe and the remaining steel surface. If the probe is scanned over a scab, at a constant offset from the surface, the lift-off will apparently increase because the distance between the steel surface and the probe has been made larger by the wall loss caused by the corrosion.

Lift-off effects can be distinguished from those due to surface defects such as cracks by the characteristics of the response obtained in the sensor coil impedance plane (see Figure A2-6).

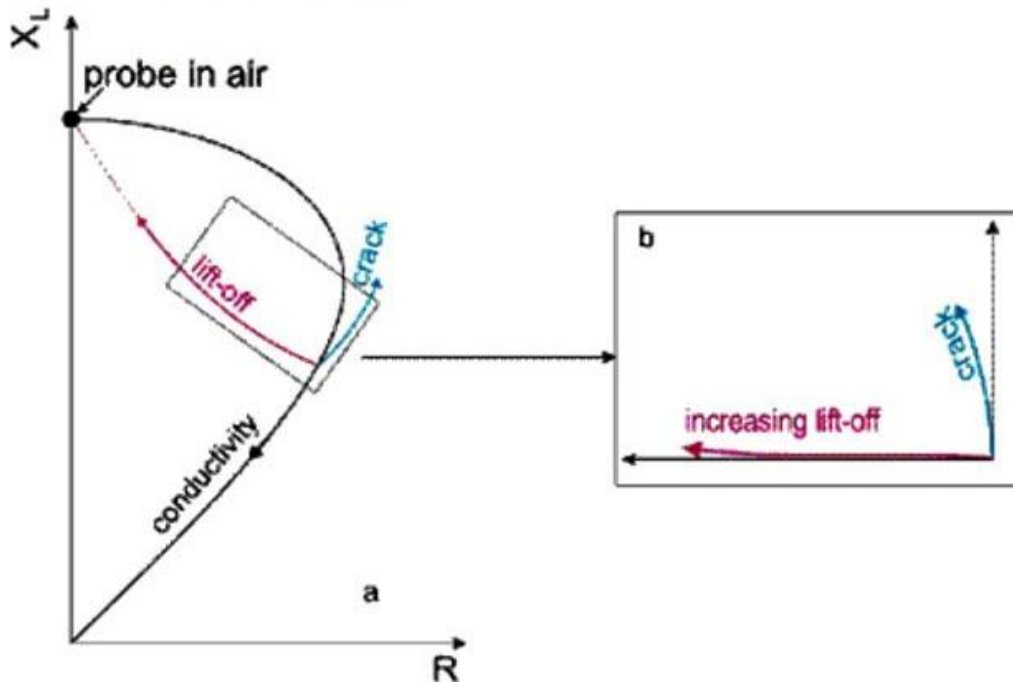


Figure A2-6: Impedance plane plot of eddy current signals showing the characteristics of lift-off and crack signals

A complication found with this approach is the presence of magnetic properties in the corrosion product, which may be present in differing amounts depending on the corrosion conditions. Magnetite is the most commonly occurring oxide of steel found in scabs that is ferrimagnetic.

In the dual frequency eddy current method, additional information is obtained that allows a correction to be made for the magnetic properties of the scab. A low frequency (typically ~100Hz) is used that can penetrate the scab material and sense the uncorroded steel surface below. In addition, a high frequency (1kHz) is used that measures the properties including scab height and magnetic properties.

A standard eddy current probe can be used, with the eddy current instrument obtaining the two frequencies on different channels. Due to the lower frequencies used, a large probe size of ~30mm is needed.

It is claimed that a combination of the two signals could be used to remove the effects of the magnetic properties of the scab, leaving only the lift-off signal. In a trial undertaken during the C17-01 project [4]), this was demonstrated on a piece of scab material that was placed between the probe and the surface, with the spot on the eddy current display remaining in the centre as this was done. However for scabs with different magnetic properties this would not necessarily be effective.

A calibration curve is then used to convert the lift-off signal amplitude into a distance between the probe and the remaining steel surface.

To maintain a constant distance above the uncorroded pipe surface, a manually operated 2-D scanner (see Figure A2-7) is used, located on the parent material around the corroded area.

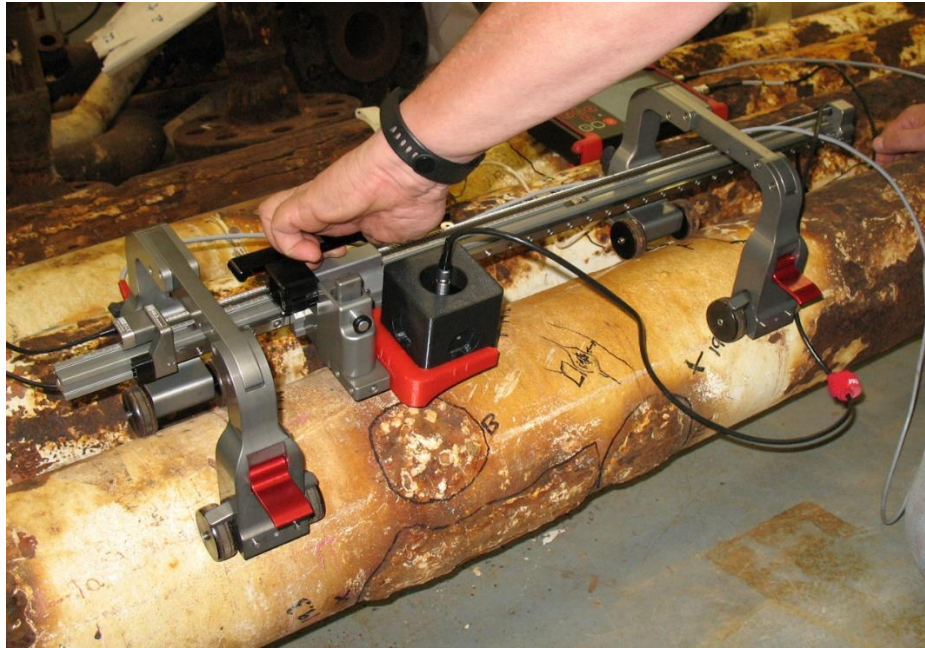


Figure A2-7: 2-D scanner being used to apply the dual frequency eddy current method to an externally corroded pipe during previous HOIS trials

With an encoded scanner, C-scan type plots can be produced for each inspection area showing wall loss as a function of axial and circumferential distance (see Figure A2-8).

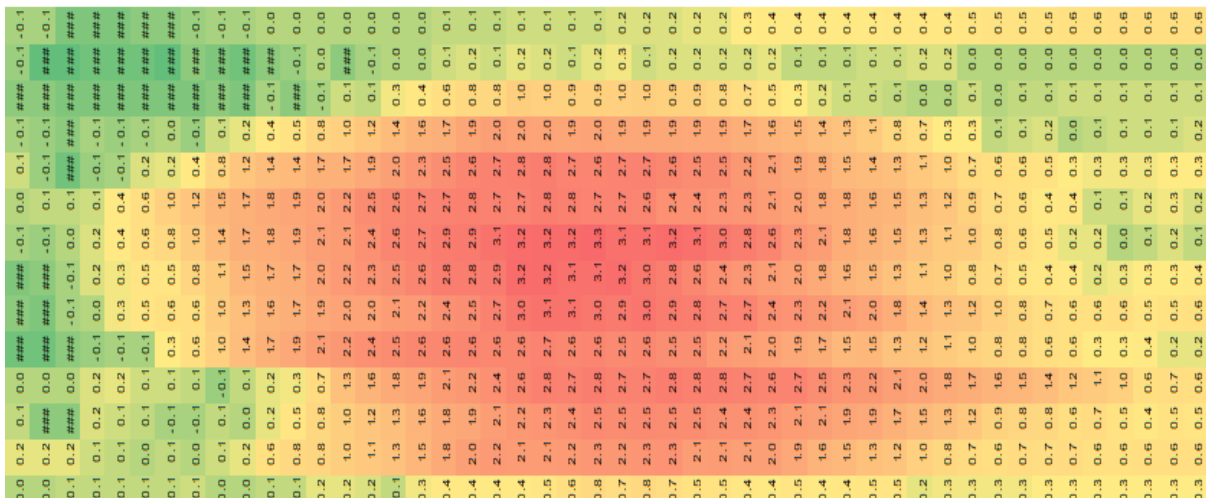


Figure A2-8: C-scan type presentation showing wall loss values obtained from a dual-frequency eddy current method for a corrosion scab

A limitation of the dual frequency eddy current method is that the compensation for magnetic properties of the scab material is based on available separate examples of scab material which are needed for calibration purposes. If the magnetic properties of the scab material on the test component differ from that of the calibration material, the accuracy of the measurements of wall loss will be adversely affected.

In the most recent HOIS trials [5], a different approach was used based on a single frequency with a phase shift correction method. The phase shift that was apparent between scabbed and

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non-scabbed areas was used in an attempt to correct for the resulting lift-off. This method had the advantage of not being dependent on calibration using a separate sample of scab material.

A2.2.3 HOIS trials

The dual frequency and phase shift eddy current methods have featured a number of developments over recent years.

The first trial of this method was hosted in 2016 [2], but the results from a trial in August 2018 [4] are considered the most representative of current state of the art for this method. On 10" sch 20 pipes with CNC areas of wall loss, the mean differences from benchmark were 1.2mm (23%) (undersizing). This systematic undersizing was attributed to sensor footprint averaging effects, due to the probe diameter of 32mm. For the thick-walled ex-service pipes, the limited number of measurements made it difficult to draw meaningful conclusions about the accuracy of this method, although the standard deviation of the differences from benchmark was 4.6mm.

For the most recent trials [5], the single frequency phase shift eddy current method was used instead, as the magnetic properties of the calibration scab material did not match those of the simulated material on the manufactured test pipes.

The trial results showed undersizing of the wall loss in the test pipes with average differences of +14% and +13% for the scabs in the two pipes, but with considerable scatter around these values. These differences were however somewhat smaller than those obtained by the same company using the Maxwell PECT equipment. It is unclear if the undersizing was due mainly to the sensor footprint averaging effects or the effects of the magnetic properties of the simulated scab material.

A2.2.4 Summary

Method:	Dual frequency/phase shift eddy current method for determining wall loss under a corrosion scab
Basis:	The eddy current method is used to provide a measurement of the lift-off between sensor and the remaining steel surface under the scab. Use of a second frequency allows a correction to be made for the magnetic properties of the corrosion product material (e.g. magnetite) provided the properties are similar to a separate piece of scab material used for calibration. The single frequency phase shift method is intended for use when a match can not be obtained between the magnetic properties of the test scab material with that of the calibration piece.
Strengths:	<ul style="list-style-type: none"> • Single sided so can be applied to vessels and pipes • Not affected by wall thickness, so equally applicable to thin-walled and thick-walled components. • For the dual frequency method, a development allowed the effects of the magnetic properties to be compensated for in real-time, allowing the point with the greatest wall loss to be found more quickly. This is however only effective if the magnetic properties of the test scab are very similar to those of a calibration sample. • The single frequency phase shift method does not require calibration using a piece of scab material with the same magnetic properties as the test scab.
Limitations:	<ul style="list-style-type: none"> • Recently developed method with limited information on performance outside of HOIS trials. • Appears to average the wall loss over the sensor size (~30mm), so can undersize localised areas of corrosion, in a similar manner to PEC. • Affected by local changes of geometry (e.g. tees). • With the dual frequency method, it is difficult to effectively compensate for the magnetic properties of the corrosion product, if samples of the product are not available for calibration purposes, or the properties vary across a single scab. • Needs sufficient areas of uncorroded material around the measurement area to allow the scanner to be deployed.
Overall:	The dual frequency method is best suited to areas of corrosion lacking localised pitting or other fine structure within the wall loss distribution. It also requires the magnetic properties of the scab material to match those of a separate calibration piece. The alternative single frequency phase shift method is more applicable when a representative calibration material is not available.

A2.3 Quantitative Short-Range guided waves (QSR1)

A2.3.1 Description of method

The basic configuration of the QSR system from GUL is shown schematically in Figure A2-9. Two EMAT transducers are used to generate and receive guided waves that propagate circumferentially around the pipe wall. The transducers are deployed at approximately the 10 o'clock and 2 o'clock positions, so there are two paths between the transducers – the short path via 12 o'clock that is generally uncorroded and the longer path via 6 o'clock which includes the potentially corroded section of pipe. The probes are scanned together in the axial direction across the region of the pipe support using a motorised drive with encoded information provided on the transducers' position.

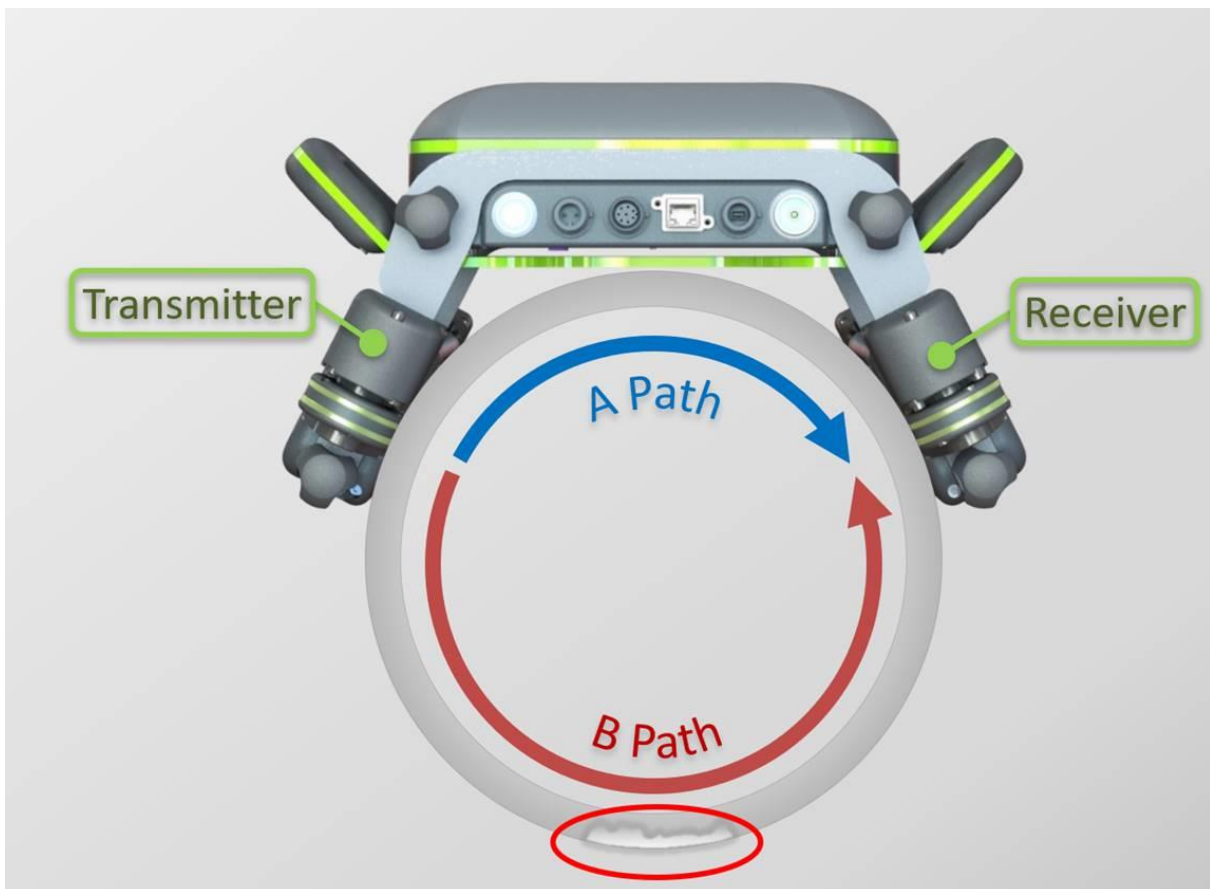


Figure A2-9: Schematic of the configuration of QSR1 (courtesy GUL)

The aim of QSR1 is to provide quantitative measurements of remaining wall thickness which is achieved by sophisticated analysis of multi-mode guided wave data. This differs significantly from the approaches used by other comparable equipment which are typically based on simpler measurements of amplitude loss and/or arrival time changes for particular wave modes. GUL have two patents pending on this method (one on the transduction, one on the analysis).

As the system is scanned along a pipe, an automated routine is used to generate a real-time profile of wall thickness (or remaining wall thickness) which is shown on a laptop connected to

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the scanner. The raw data is also stored and is then available for review and offline manual analysis after the scan has been completed.

According to GUL, the main current limitations of the QSR1 for sizing are expected to be:

- If the wall loss is greater than 50%, the value provided will not be quantitative, but should be reported as >50%.
- The probe beamwidth is stated to be 40mm but the instrument is said to be capable of reliably sizing localised areas of wall loss down to ~25mm in axial extent. Corroded areas smaller than this are likely to be undersized.

A2.3.2 Equipment

The QSR1 scanner is shown on a pipe in Figure A2-10. It is motorised to allow automated axial scanning along a pipe, with an encoder for positional feedback. The whole system is battery operated.



Figure A2-10: QSR1 scanner on a pipe (courtesy GUL)

A2.3.3 Application to scabs

The QSR1 guided wave method has been applied to scabs with the aim of determining the minimum remaining ligament in the corroded area. The method is rapid, requiring only a single axial scan to inspect the scab. The use of EMAT probes does not require ultrasonic couplant and is more tolerant to poor surface condition than conventional ultrasonic probes.

However, because the method requires access to the full pipe run for positioning and operation of the scanner, the technology would not be applicable for scabs that are fully circumferential around the pipe, nor for scabs that are nearly fully circumferential.

Note however that a circumferential scanning, axial beam version of QSR is due early 2022 and would allow inspection of a fully circumferential scab, provided there is sufficient uncorroded material on both sides of it.

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The footprint of uncorroded metal required around the scab to allow positioning and scanning of the QSR1 scanner is substantial, and so the equipment is likely only to be applicable to relatively isolated, reasonably compact scabs.

QSR1 is said to be unaffected by liquids, either on the inside or outside of the pipe due to the wave modes used.

There are issues when there are long areas with very rough surfaces, which cause substantial signal attenuation. Current developments involve increasing signal amplitudes to compensate for this.

Currently the method is applicable to pipes with diameters between 6" and 24" and nominal wall thicknesses between 6mm and 13mm. The upcoming introduction of the axial beam tool will reportedly decrease the minimum inspectable diameter to 3 inches. In addition the maximum thickness will increase to 25mm. GUL are also developing machine learning analysis which is currently being trialled.

A2.3.4 HOIS trials

In April 2018, a QSR1 HOIS trial took place on a 10" sch 20 pipe, into which advanced CNC machining methods had been used to introduce areas of wall loss having morphologies based on those found in examples of service induced scabs provided previously by a HOIS member. These pipes were manufactured because the original ex-service pipes had been used for previous HOIS trials but were not available for the present trials.

For the pipe scanned by QSR1, all the CNC areas of wall loss had been arranged with a common circumferential location but spaced axially along the pipe. This allowed the areas to be centred at 6 o'clock with the scanner deployed at 12 o'clock. It was found that QSR1 could not be deployed on the other 10" sch 20 CNC pipe, which had CNC areas distributed both axially and circumferentially. This was because no clear path could be found to deploy the QSR1 scanner on this pipe, in between the CNC areas.

The QSR1 trial gave encouraging levels of agreement with the benchmark values for minimum remaining ligament for the limited number of areas of wall loss in the CNC machined 10" sch 20 pipe (6.4mm nominal wall thickness) with all the areas centred at 6 o'clock. For the QSR1 trial, of the seven areas of wall loss inspected, one was reported as having a wall loss of >50%, which was consistent with the benchmark value. Quantitative values for remaining ligament were reported for the remaining areas and these showed a mean difference from benchmark of 0.0mm (-0.3%WT), and the standard deviation of the values was 0.3mm (5% WT). The largest undersizing (positive difference) was only 0.5mm (7.7% WT).

In the most recent trial in February 2021, two pipes (10" NB / Sch.60) exhibiting areas of CNC-machined wall loss based on corrosion from ex-service pipes were assessed^[5]. As the main focus of this latest project was to assess the effectiveness of NDT techniques in determining the minimum remaining ligament of scabs containing localised pitting, both pipes exhibited varying degrees of localised pitting within regions of otherwise more general wall loss. A mixture of modelling clay and crushed magnetite, which is ferrimagnetic, was applied to each area of wall loss to simulate scab material. It should also be noted that the areas of wall loss on both pipes were spaced along each pipe at the same circumferential location.

Assessment of the pipes with QSR1 resulted in the best performance of the techniques trialled in the study. A maximum undersizing of 12.3%, a maximum oversizing of 16.8%, and an average of -0.1% for the first pipe (which contained scabs with multiple localised pits) were

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achieved. For the second pipe, which contained scabs with single localised pits, the maximum undersizing was 23.4%, the maximum oversizing was 1.7%, and the average was 10.9%. When the deepest isolated pits were omitted from the second pipe (by altering the benchmark values to reflect the remaining wall thickness excluding the additional localised pits), the maximum undersizing, maximum oversizing and average values were 7.6%, 9.0% and -1.2%, respectively. This therefore suggests that the isolated machined pits for this pipe were not detected, as they were presumably substantially less extended than the sensor footprint dimension. Despite the reduced undersizing for pipe 1, it is unclear if the multiple localised pits in pipe 1 were detected, as there was no evidence of them in the axial profiles of remaining ligament generated by QSR1.

Additionally, for four of the six scabs, the benchmark wall losses were <50% and the QSR1 results correctly gave quantitative values for these scabs. For the remaining two scabs, one had a benchmark value of very slightly more than 50%, but the value from the QSR1 trial was quantitative with no indication of an uncertainty due to the wall loss being >50%. More significantly, this was also the case for the second of these two areas, despite the benchmark value for wall loss being >55%.

For the second pipe, one of the areas was correctly reported as >50% wall loss, which was consistent with the benchmark value. However, of the remaining areas of wall loss, one had a wall loss of very slightly more than 50% and another had a wall loss of about 60%. Neither of these areas were reported by the trialist as having a wall loss >50%, and for the area of wall loss of ~60%, the QSR1 value had the largest undersizing of this trial (+23.4% difference from benchmark).

A2.3.5 QSR1 summary

Method:	QSR1
Basis:	Uses two EMAT probes to generate a circumferential beam of guided waves. Scabs cause changes in the GW signals obtained using this device, which are then analysed using a sophisticated multi-mode analysis method.
Strengths:	<ul style="list-style-type: none"> • EMAT probes less affected by surface condition/coatings than conventional ultrasonic probes. • Rapid inspection. • Quantitative indication of defect severity for wall losses less than 50%. • Highest sizing accuracy of methods trialled in HOIS for 10" sch 20 (6.4mm nominal wall thickness) pipes with CNC areas of wall loss, and for 10" sch 60 (12.7mm nominal wall thickness) pipes with CNC areas of wall loss and multiple localised pits.
Weaknesses:	<ul style="list-style-type: none"> • Not applicable to fully circumferential scabs nor those that are nearly fully circumferential. • Requires a substantial area of uncorroded pipe material around the scab for positioning of the scanner, hence only applicable to reasonably localised, isolated scabs. • The probe beamwidth is stated to be 40mm but the instrument is said to be capable of reliably sizing localised areas of wall loss down to ~25mm in axial extent. Corroded areas smaller than this are likely to be undersized. • Does not provide quantitative sizing information for wall losses > 50% WT. • Insensitive to highly localised pitting which, if present, can result in undersizing, as shown in the recent HOIS trials.
Overall:	A promising method for quantitative sizing of remaining ligament for scabs on pipes with diameters between 6" and 24", and nominal wall thicknesses between 6mm and 13mm, provided the scanner can be deployed and operated on uncorroded areas on the pipe. Localised pitting can cause undersizing as the pits may not be detected due to the probe beamwidth size.

A2.4 Multi-skip/M-skip®

A2.4.1 Description of method

Multi-skip/M-skip® is an ultrasonic method that was developed in the mid-2000s [7]. Multi-skip/M-skip® is based on angled pitch-catch shear wave probes, to avoid mode conversion losses at reflections from the component surfaces. These probes can be separated by the distances required to inspect some scabs. The signals travelling between the probes then typically experience many reflections, or skips, between the front and back component surfaces.

Figure A2-11 illustrates the concept of the method for inspection of corrosion scabs. Only the discrete ray paths corresponding to strong reflected signals are shown, but it should be appreciated that the transducers transmit and receive ultrasound over a continuous range of angles governed by the probe beam spread.

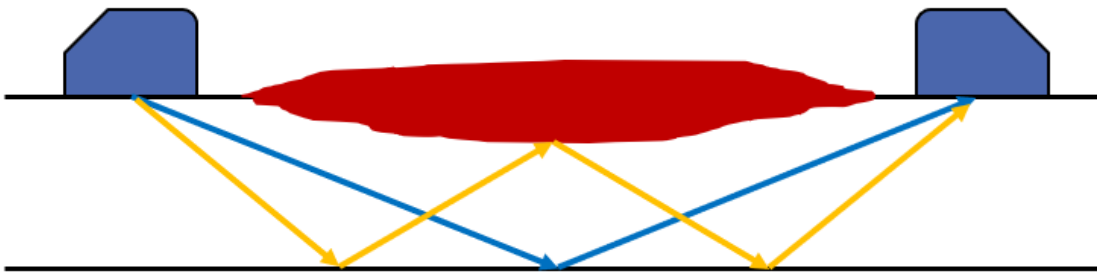


Figure A2-11 Concept of the Multi-skip/M-skip® method showing the ray paths for the first two signals between the transmitter (Tx) and the receiver (Rx) for external corrosion

For a given probe separation and wall thickness, there are several different ray paths between the probes, involving different numbers of surface reflections. The shortest path involves a single reflection from the backwall. The next signal (skip 2) to arrive involves two reflections from the backwall and a single reflection from the front wall. The total number of signals detected at the receiving probe will depend on the probe beam width, the probe separation, and the wall thickness. Depending on the probe separation and wall thickness, the first few signals will not necessarily be detectable, as they may involve very high probe angles.

The arrival times of the Multi-skip/M-skip® signals can be analysed to provide quantitative estimates of wall loss.

For scab inspection, Multi-skip/M-skip® can be applied using the following scan modes:

- Circumferential scans using axial beams (see Figure A2-11)
- Axial scans using circumferential beams (see Figure A2-12).

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Axial beam scans allow the method to be applied to fully circumferential scabs. Where possible, combination of both axial and circumferential scans improves the reliability of the sizing information obtainable with the method. This was further illustrated in the recent HOIS C19:01 trials [5].

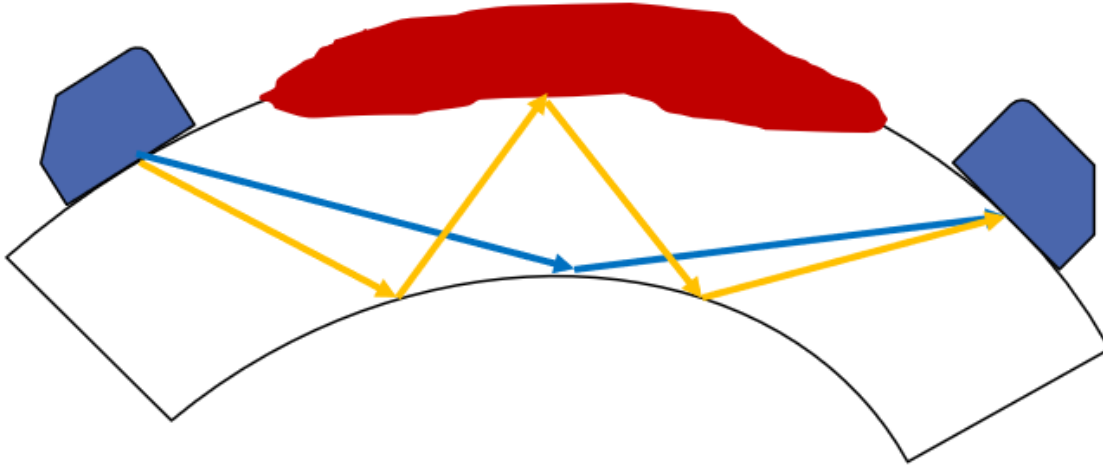


Figure A2-12: Schematic of circumferential beam Multi-skip/M-skip® showing the first two skip signals (1 and 2). Where possible, sizing should be based on skip 2 (orange propagation path).

A2.4.2 Application to external corrosion scabs

Applications of M-skip to date on external corrosion scabs, have been based on the usage of skip 2 to size the wall loss, as this provides a single reflection from the corroded area, and avoids any multiple-counting effects that can lead to over-estimates of wall loss for higher skip numbers.

Note that the measurement of the wall loss is obtained for a position midway between the probes. If the deepest point is significantly offset from the centre of the scab, this will result in undersizing. This can be minimised by use of a combination of both axial beam and circumferential beam scanning on the same scab and use of the greater of the two wall loss values found from these scans. Scans made with the probes offset from the centre of the scab can also be made to provide additional measurements of the wall loss under the scab, with the largest value taken as an estimate of the maximum wall loss.

For skip 2 signals to be used, the optimum probe separation is ~ 11 WT, where WT is the uncorroded pipe wall thickness, but it has been found that this can usually be increased to about 18 WT without significantly adverse effects. For higher probe separations, skip 2 signals are generally no longer evident, and cannot be used for sizing.

Hence the extent of the corrosion scab, in the direction of the ultrasound beam, must not exceed ~ 18 WT (or slightly less to allow the probe to be placed on the parent metal either side of the scab, and for there to be a separation between the probes and the edges of the scab to allow for probe scanning).

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One limitation is that, in common with other ultrasonic methods, Multi-skip needs the surface under the probes to be relatively free from loose scale.

Multi-skip/ M-skip® is better suited to inspection of relatively thick-walled components (at least 10mm, with >15mm better). For corroded components, especially those with thinner walls, the Multi-skip signals may disappear completely due to scattering at the rough surface, resulting in loss of sizing information.

A2.4.3 HOIS trial experience

Previous M-skip trials on thicker-walled test pipes (10" sch 80, 15.1mm WT, with CNC machined areas of wall loss and the 6" sch 160, 18.3mm WT, ex-service pipes) showed generally close agreement with the benchmark values, as did the previous trials already reported [4].

For the CNC machined pipes, the mean difference was 0.0mm and the standard deviation of the values was only 0.5mm (3% WT). The largest undersizing (positive difference) was only 0.4mm (3% WT). Unexpectedly, the largest difference was an oversizing of 1.1mm (8% WT).

However, for the ex-service pipes, the mean difference was +1.0mm (undersizing) and the standard deviation of the values was 0.9mm (5% WT). The largest undersizing (positive difference) was 2.7mm (15% WT). This occurred for one of the areas of wall loss shown to contain pronounced highly localised pitting, which had evidently not been detected in the M-skip data.

M-skip was the most accurate method in HOIS trials for thicker walled pipes, for areas without highly localised pitting, but can only be applied to scabs with extents up to about 18 times the wall thickness, surrounded by parent material with adequate surface condition.

Severe corrosion can cause complete loss of signal and hence no sizing information. The method may also fail to detect some areas of highly localised pitting, superimposed on larger areas of corrosion, which can lead to undersizing (maximum of 2.7mm for the ex-service scabs in the 6" sch 160 pipes).

The most recent M-skip trial in late 2020 [5] was performed on two 10" pipes each with a nominal wall thickness of 12.7mm (sch 60). As the main focus of this latest project was to assess the effectiveness of NDT techniques in determining the minimum remaining ligament of scabs containing localised pitting, both pipes contained varying degrees of localised pitting in otherwise more general areas of wall loss. A mixture of modelling clay and crushed magnetite, which is ferrimagnetic, was applied to each area of wall loss to simulate scab material.

For the first pipe, with the multiple isolated pits, M-skip gave a maximum undersizing of 25.5%, a maximum oversizing of 0.1%, and an average difference of +6.8% (undersizing). It must be noted that for five of the six areas of wall loss, both circumferential and axial measurements were taken, whilst only a circumferential measurement was taken for the remaining area of wall loss (due to its extent) which had the largest undersizing of 25.5%. When the circ. only measurement was removed, the maximum undersizing was 9.7% and the average was +3.1% (undersizing). This highlights the importance of taking both axial and circumferential measurements, when possible.

For the second pipe, with the single localised pits, the maximum oversizing was 25.1%, the maximum undersizing was 12.2%, and the average was 20.5%. Due to the extents and axial

spacing of the scabs, only four of the six scabs could be measured and it was only possible to take both axial and circ. measurements from one of the measured scabs. The undersizing from the scab with both axial and circ. measurements was 12.2% which is a significant improvement from the maximum undersizing value when all scab measurements were used. The larger undersizing values for pipe 2 were attributed to the lack of detection of the single isolated pits, which were appreciably smaller in extent than the probe beamwidth. In addition, some of the undersizing for pipe 2 was probably caused by the larger extents of the scabs, which allowed collection of only one scan for all but one of the scabs measured.

A2.4.4 Multi-skip/M-skip[®] summary

Method:	Multi-skip/ M-skip [®] pitch-catch UT
Basis:	Uses two shear-wave pitch-catch ultrasonic probes. Corroded areas are sized by a change in signal arrival time.
Strengths:	<ul style="list-style-type: none"> • Quantitative sizing demonstrated in trials in thicker-walled components (> about 15mm). • Axial beam variant applicable to fully circumferential scabs. • Combination of axial and circumferential beam scanning provides more confidence in results and reduced undersizing. Offset scans can also be used to provide additional measurements of wall loss which should increase the accuracy in the derived overall maximum value. • Rapid scanning.
Weaknesses:	<ul style="list-style-type: none"> • Only applicable to scabs with a maximum extent in the axial or circumferential direction of at most 18WT. • Can be affected by surface roughness and poor surface condition (coating etc.) around the scab, resulting in loss of signal responses. • Sizing generally possible on thicker walled pipes only (>15mm). • Sizing information subject to uncertainty depending on the corrosion morphology and the location of the deepest wall loss relative to the probes' centre line. • Complete loss of signal (no sizing information) may occur for thin walled components (<10mm WT) with only moderate levels of scabs. • Insensitive to highly localised pitting which, if present, can result in undersizing, as highlighted in the most recent HOIS trials.
Overall:	In HOIS trials this technique has shown good sizing accuracy for thicker-walled components (greater than about 15mm WT) for scabs lacking localised pitting. The method can, however, undersize corroded areas with significant, highly localised pits and areas for which the combination of both circumferential and axial beam scans are not possible.

A2.5 Radiography

A2.5.1 Overview

There are various different approaches to industrial radiography for inspection of corroded pipes, based on different radiation sources and detectors and configurations of these sources and detectors.

However, to provide estimates of the remaining wall thickness under external corrosion scabs, only tangential radiography is applicable. Other techniques such as double wall radiography (DWRT) cannot be used to provide estimates of remaining wall thickness under a corrosion scab, but has shown in a recent, limited trial that it can provide information on the presence of highly localised pits that can be present in some corroded areas [6]. This information could be valuable in indicating that other NDT methods with more limited spatial resolution will undersize the extent of the wall loss for these highly pitted corroded areas.

Radiography for scabs (both film and digital) should be performed in accordance with the international standard ISO 20769: Part 1 (see also the HOIS RP for in-service digital radiography [8]).

A2.5.2 Radiation sources for radiography

For in-service site radiography, isotope radiation sources are generally used. The most commonly used source is Iridium 192, but others include Cobalt 60 and Selenium 75. Iridium 192 gives gamma rays with a mean energy of about 340 keV. Selenium 75 has a lower mean energy of about 220 keV which gives higher radiographic contrast for thinner walled components. However, Se75 is significantly less penetrating than Ir 192, a disadvantage for the tangential method. Hence Se 75 is less widely used than Ir 192.

Cobalt 60 gives gamma rays with a significantly higher mean energy than both Ir 192 and Se 75 (c. 1250 keV) which allows penetration of thicker components. However, the radiological safety issues associated with the use of this high energy source are substantial, and for this reason it is seldom used in the UK and Europe. Use of Co 60 is more widespread in the USA.

Isotope sources are often housed in shielded containers from which the active pellet must be withdrawn to perform the radiography. Manual winding methods are usually used, and the pellet is moved rapidly along a flexible tube from the container to the position for radiography. Often a collimator is used to limit the angle over which the radiation is emitted, to reduce the general dosage in the surrounding area and back-scatter on the radiograph.

Alternative source containers with integrated collimators are available for Ir 192 and Se 75 sources. Their advantage is that the source remains within the container and a narrow beam collimator substantially reduces the size of the controlled area needed around the source. Such systems are generally referred to as small controlled area radiography (SCAR) and can reduce radiation safety issues and associated impacts on site operations and alarms.

Portable X-ray sources (some are battery powered and pulsed) are increasingly being used for in-service inspection, due to higher available kVp than previously. An advantage of X-ray sources is that the ionizing radiation can be readily switched off, unlike isotope sources. The most recent HOIS study [6] assessed the use of pulsed X-ray in determining the presence of isolated pitting under external corrosion scabs.

In addition, much higher energy (MeV range) portable Betatron sources, have also been used for certain specialised applications in the oil and gas industry that require greater penetration than is possible with Ir 192. Examples have included offshore deployment for below deck inspection of thick-walled, large diameter pipes. Compared with isotope sources, Betatron sources can be readily switched off which avoids the onerous regulations associated with storage and transportation of isotope sources.

A2.5.3 Detectors for radiography

Conventional film radiography is still often used, but various forms of digital detectors are becoming more widespread. Digital radiography methods can have advantages over film methods in terms of shorter exposure time, reduced costs, and increased exposure latitude. They can be broadly grouped into:

Computed radiography (CR):

The film is replaced by a photostimulable phosphor imaging plate (IP) which is subsequently read out using a laser scanner. This is a two-stage process not dissimilar to exposure of film, followed by development.

Digital Detector Arrays (DDA):

The film is replaced by a two-dimensional array of detectors that produce an image that can be directly read out. This is a more rapid single stage process than CR and generates near real-time images.

Within the field of in-service inspection for external corrosion, CR based on re-usable imaging plates has now been used for several years. Its advantages over film include somewhat reduced exposure times, and, for tangential radiography, the availability of interactive software tools for direct measurement of remaining wall thickness on the CR images.

There is also increasing interest in, and usage of, digital detector arrays (DDAs). These are more sensitive than film and the imaging plates used for CR, and hence allow significantly reduced exposure times. However, DDA's are high capital cost items and are fragile (likely to break if dropped). Nevertheless, in the last few years, there has been increased site usage of these detectors.

In some cases, DDA panels can offer substantial reductions in exposure times over those used with film or CR, typically by factors of up to 5-10. However, a large part of the time taken for site radiography is in the setup of the exposure, so that a substantial reduction in exposure time may not necessarily lead to a correspondingly large increase in the coverage achieved in a certain time.

A2.5.4 Tangential radiography technique

The overall configuration of source and detector for tangential (sometimes called profile) radiography, is shown in Figure A2-13. The radiation source is well removed (stood-off) from one pipe wall and the flat detector is positioned on the opposite side of the pipe, generally in contact with the pipe or as close as possible to it.

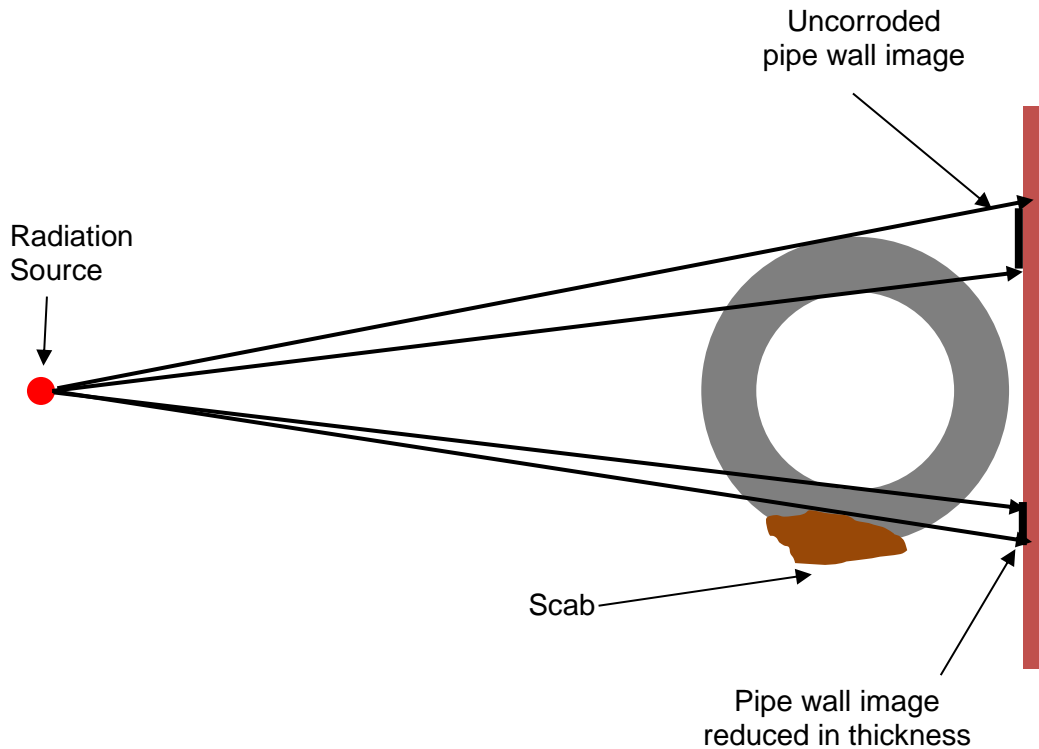


Figure A2-13: Schematic of tangential radiography for scab inspection with the source aligned with the pipe axis

With tangential radiography an image of the pipe wall is obtained, allowing measurement of the minimum remaining wall thickness, provided the most corroded area is accurately aligned with the tangent position. Such accurate alignment may be difficult given on-site conditions and limitations over positioning of the source and detector.

For tangential radiography, the maximum tangential path, w_{max} , through an uncorroded steel pipe wall is given by

$$w_{max} = 2\sqrt{WT(OD - WT)} \quad (A2.2)$$

Where

WT is the wall thickness
OD is the pipe diameter

For tangential radiography using Ir 192, the maximum steel equivalent tangential path is about 80mm (see ISO 20769:1).

For this reason, tangential radiography is most commonly applied to small diameter pipework (e.g. 3" nominal bore and smaller), although the tangential method can be extended to larger diameter pipes provided the maximum tangential path (chord length) given in the equation above is less than the limit for the source in use. With Ir 192, a 6" schedule 40 pipe is on the limit of applicability for tangential radiography.

An alternative configuration of source location for larger diameter pipes is shown in Figure A2-14. This has the radiation source offset from the pipe axis and instead aligned with one of the pipe walls. In this case it is important to use a dimensional comparator of known diameter, as shown, to provide dimensional calibration of the radiographic images. [Dimensional comparators can also be used for smaller bore pipes to avoid the need to use the pipe OD for calibration].

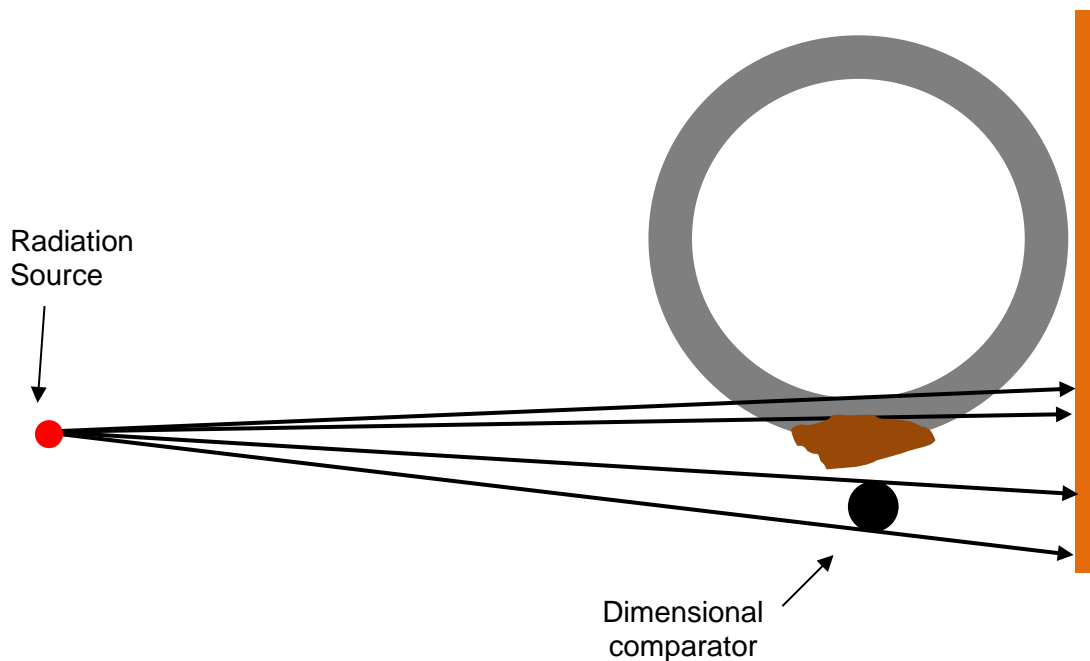


Figure A2-14: Schematic of tangential radiography for scab inspection with the source offset from the pipe axis

The reliability of the measurements of remaining ligament obtained with tangential radiography can be affected by the morphology of the corrosion (Ref. [8]; ISO 20769-1). Reliable sizing is usually only obtained for extended areas of corrosion, without localised pitting, which present a uniformly convex shaped external steel surface profile. If localised pitting is present then the external profile is unlikely to be convex and the measurements of remaining ligament are potentially unreliable (see Ref. [9] and ISO 20769-1).

With tangential radiography, depending on the source strength, source to detector distance etc, the exposure time required can be several minutes, with a longer setup time. Use of imaging plates (CR) or DDAs instead of film allows some reduction in exposure time.

Usually throughput is of the order of 1 exposure an hour during in-service inspection of typical oil and gas plant (when averaged over a typical shift, with multiple locations).

A2.5.4.1 Application to Scabs

In service inspection of externally corroded pipes using tangential radiography is covered by the standards ISO 20769 Part 1 and a HOIS RP [8]. Any radiography for scab inspection should be performed in accordance with these documents.

The main advantage of tangential radiography for scab inspection is that it is one of very few methods capable of providing a quantitative measurement of the remaining steel wall thickness, provided the worst affected area is accurately aligned with the tangent position. For reliable measurements of remaining ligament, multiple exposures are needed at different angular positions, as described in the HOIS RP for in-service radiography (ISO 20769-1 and Ref. [8]).

Note however the caveats on sizing of external corrosion, contained in the HOIS safety notice on this topic [9] and in ISO 20769. This shows that for some corrosion morphologies (mainly those with localised pitting) significant under-estimates of the wall loss are likely to be obtained when using tangential radiography.

The ability of tangential RT to be used to inspect bends, tees and other complex geometries is particularly valuable. This is illustrated in Figure A2-15 which shows a radiograph of a heavily externally corroded complex assembly including a valve and a reducer pipe section. The areas highlighted show where there is negligible remaining wall thickness.

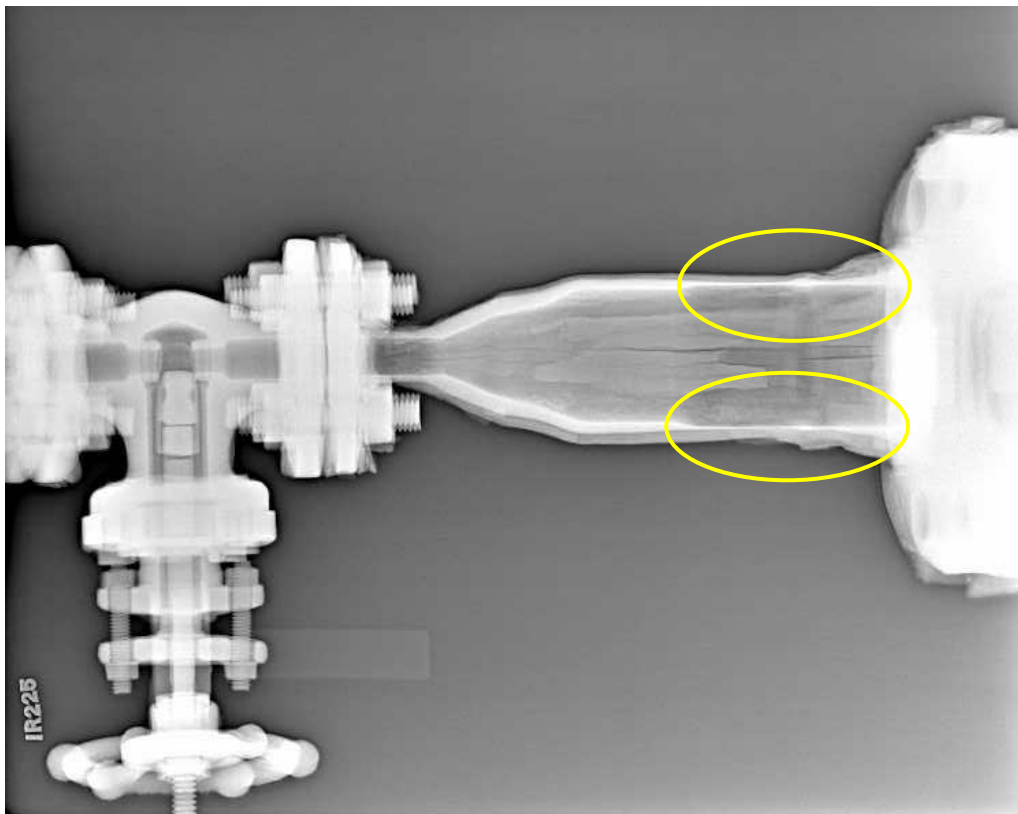


Figure A2-15: CR image of a pipe assembly including a valve, reducer section and a short length of 2" pipe. The reducer pipe section has heavy external corrosion and the radiograph clearly shows very little remaining wall thickness in the areas highlighted.

A further example of a CR image of an externally corroded component is given in Figure A2-16. This shows a 10" sch 20 pipe with a substantial external corrosion scab, with the corrosion

product in-situ. This image was obtained with the offset source position illustrated in Figure A2-14. In this case, the area of corrosion was extended and reasonably uniform and had a convex shaped external steel profile. The resulting measurement of remaining wall thickness (1.6mm) then agreed well with the benchmark value.

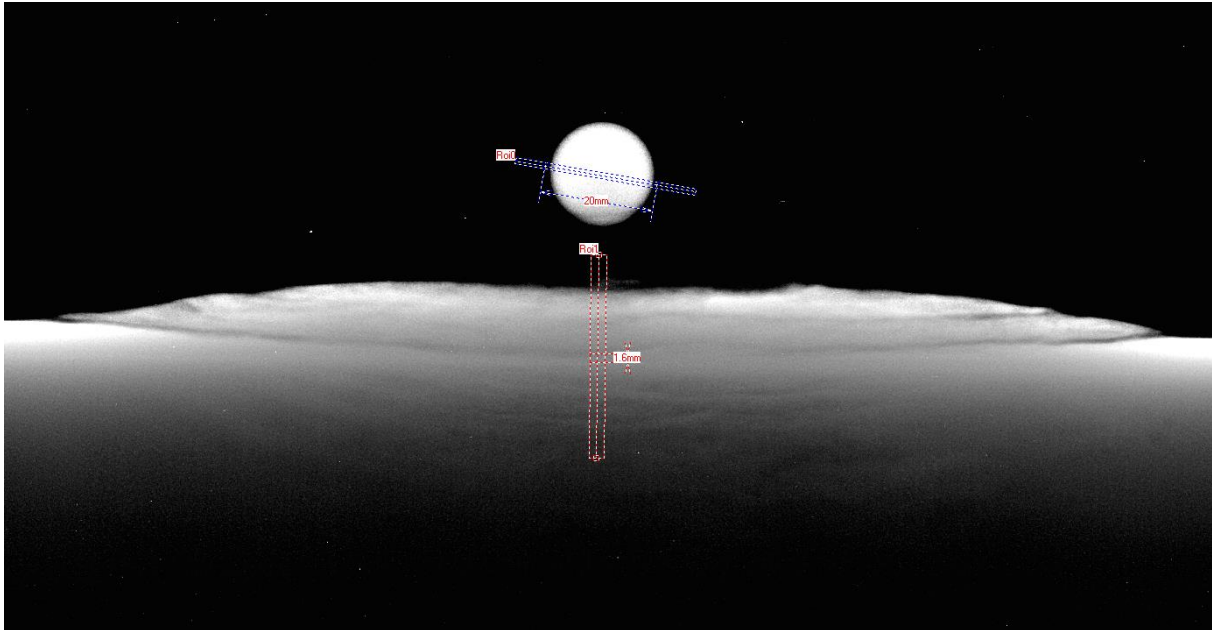


Figure A2-16: CR image of a scab on a 10" sch 20 pipe showing ball bearing comparator used for dimensional calibration and determination of the minimum remaining wall thickness (c. 1.6mm)

A2.5.4.2 HOIS trial results

An extensive series of multi-vendor HOIS radiography trials were performed over a significant period of time, which underpinned the development of a HOIS RP for in-service digital radiography [8]. This led to the development of the international standard EN 16407 parts 1 and 2, which were superseded in November 2018 by ISO 20769 Parts 1 and 2.

A summary of the HOIS radiography trial results obtained on externally corroded components, mostly ex-service, is given in the HOIS RP [8].

A summary of differences between the radiography results and the benchmarking, taken from this report, is given in Table A2.1.

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Table A2.1: Summary of the Digital RT results for the externally corroded pipe specimens

Specimen/ Scab	Corrosion type	Pipe schedule and wall thickness (mm)	Minimum wall thickness (mm)		Difference (radiography – benchmark) (mm)	Difference (radiography – benchmark) (% of nominal WT)
			Benchmark	Digital radiography		
H129	Localised circumferentially	6" sch 40 (7.1 mm)	1.9	3.5	1.6	23
H168	CUI – extended circumferentially	6" sch 40 (7.1 mm)	1.3	1.5	0.2	3
H185	General & fine pitting	3.8	1.3	2.6	1.3	34
H186 scab 1	General only	5.5	2.2	2.4	0.2	4
H186 scab 2	General only	5.5	2.7	2.4	-0.3	-5
H187	General & fine pitting	3.9	1.8	2.8	1.0	26
H210 Scab 1	External scab (convex profile)	10" sch 20 (6.4 mm)	≤1mm	c. 1.1	c.0.1	c. 2
H210 Scab 2	External scab (convex profile)	10" sch 20 (6.4 mm)	≤1mm	c. 1.6	c.0.6	c. 9

From the above table, it can be seen that for five of the scabs (H168, H186 scabs 1 & 2 and H210 scabs 1 & 2), there was good agreement between benchmark and the tangential radiography measurements of minimum remaining wall thickness (with differences of ≤0.6mm), whereas for the other three scabs (H129, H185 and H187), there were significantly larger differences of between 1.0mm and 1.6mm.

The issues causing the larger differences were believed to be as follows:

1. The circumferentially localised scab on pipe H129 which caused the outer profile of the remaining steel wall to be concave, instead of the convex shape of a pipe OD.
2. The fine pitting, superimposed on more general wall loss/corrosion, for the scabs in H185 and H187. This was not detected on the tangential radiography image and hence not sized.

As an example of these results, for specimen H129, a representative DR image obtained using a GE DXR250V DDA with the tangent position close to the position of minimum ligament is shown in Figure A2-17.

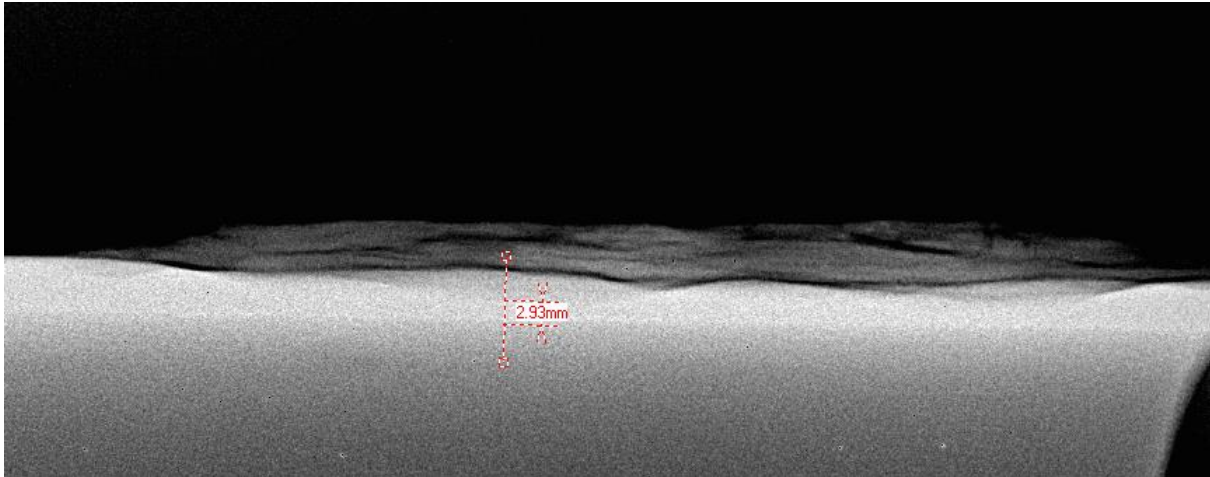


Figure A2-17: Magnified and enhanced DR image of the scab section of specimen H129 showing an alternative interpretation using internal pipe wall features which give a smaller remaining wall thickness

The digital radiograph given above clearly shows the presence of structure in the image of the pipe-wall, which is an indicator of localised corrosion that can lead to unreliable sizing, as described further in the HOIS RP [8] and ISO 20769:1.

An example of a corroded area that gave good agreement between the tangential RT value for remaining wall thickness and benchmark is shown in Figure A2-18. This gives a representative DR image obtained with a GE DXR250V DDA. Here the tangent position was closest to the position of the minimum ligament. Note for this scab, there is no structure visible within the two pipe wall images.

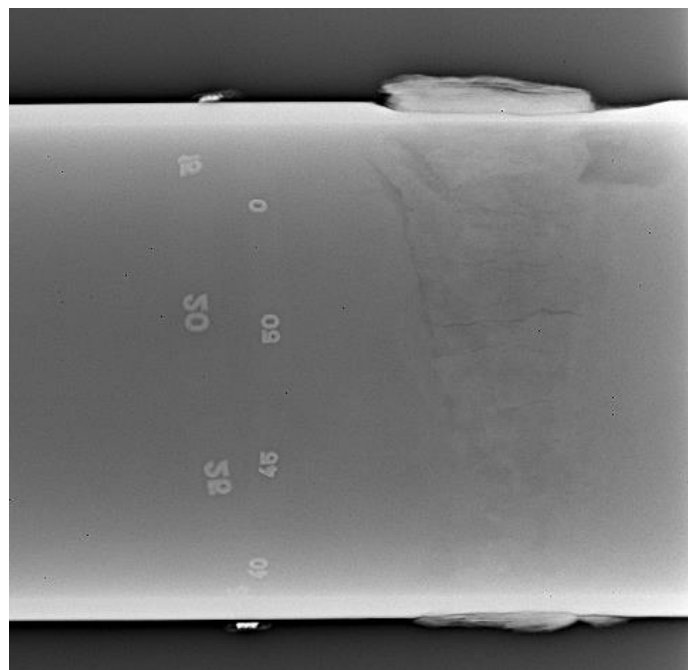


Figure A2-18: DR image of the scab section of specimen H168, close to the angle showing the greatest wall loss/minimum remaining wall thickness. Note the lack of structure in the images of the pipe walls.

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For H168, the total circumferential extent of the corrosion was $>180^\circ$, whereas it was only $\sim 30^\circ$ for H129.

The shapes of the outer edge of the uncorroded steel derived from the UT and DR measurements are shown in Figure A2-19. From this figure it can be seen that the external profile was largely convex, unlike that for H129 which was concave.

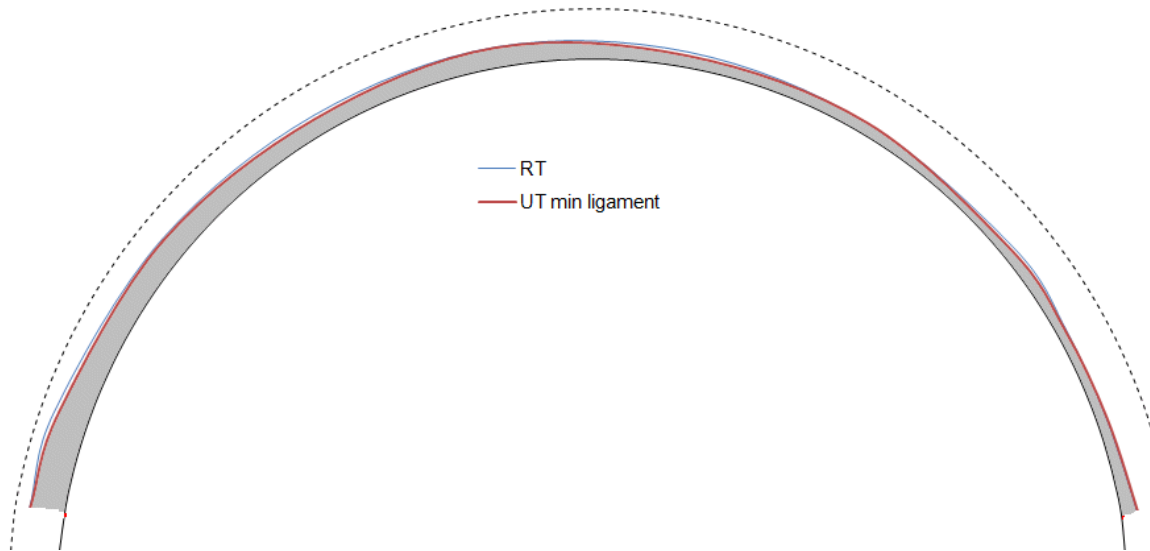


Figure A2-19: The shape of remaining metal under the scab in pipe H168 derived from the UT benchmark data and the DR measurements

The results for H168 show that for this convex shaped area of corrosion there was very good agreement between the DR measured minimum remaining ligament and the corresponding UT benchmark value, whereas for the concave shaped remaining metal under the scab in H129, significant errors were found.

A2.5.4.3 Summary

Method:	Tangential radiography to measure remaining wall thickness
Basis:	Radiographs show the presence of wall loss due to CUI at the tangent position and the associated corrosion product. Quantitative measurement of remaining wall thickness can be obtained in some cases depending on the corrosion morphology.
Strengths:	<ul style="list-style-type: none"> Quantitative wall thickness measurements for scabs with appropriate corrosion morphologies (lack of localised pits, leading to a convex external steel surface). Applicable to changes in geometry (bends, reducers, tees etc.).
Limitations:	<ul style="list-style-type: none"> Radiation safety issues. For measurement of remaining ligament, restricted to 6-8" pipes (sch 40/80) and those with smaller diameters/wall thickness (chord length no more than about 85mm) if using Ir 192. Unreliable measurements of remaining wall thickness for any scabs having corrosion morphologies that have localised pitting features, giving concave external surfaces (recognised by structure in the image of the pipe wall). Not applicable to vessels.
Overall:	A method applicable to small bore pipes, including those with complex geometries. Important to note the likelihood of unreliability in measurement accuracy for any corroded areas with localised pitting, which can be recognised by the presence of structure in the radiographic image of the pipe wall.

A2.5.5 Double-wall single image (DWSI) method

The overall configuration of source and detector for double wall single image radiography, is shown in Figure A2-20. The source is positioned close to one pipe wall, and the detector is usually wrapped around the opposite side containing the external corrosion scab. This technique is generally used for larger diameter/wall thickness pipes than DWDI/tangential radiography.

Wall loss under the scab can be detected by its effect on the image density (or grey levels in a digital image). As with DWDI, this method does not provide a quantitative measurement of the through wall extent of the wall loss. The presence of associated corrosion product will reduce the overall contrast of the corroded area, making it more difficult to detect reliably.

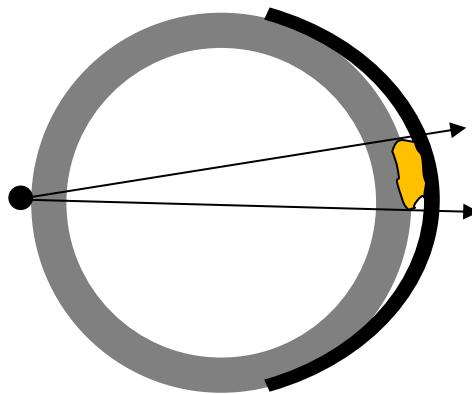


Figure A2-20: Schematic of double-wall single image radiography for scab inspection

Depending on the source strength, source to detector distance etc., the exposure time required for DWSI is usually much less than for DWDI/tangential radiography but the setup time is similar. Again, use of imaging plates (CR) instead of film allows some reduction in exposure time but will not lead to much improvement in overall inspection time which is dominated by the setup time.

A2.5.5.1 Application to scabs

In practice, the external surface of the corrosion product does not contain directly corresponding outwards projections due to the presence of the localised pitting in the steel substrate beneath the scab. Hence isolated fine pitting will cause less radiation attenuation than the surrounding areas and this will then be visible as areas with reduced attenuation (darker indications) on the corresponding radiographs, assuming the conventional negative representation of radiographic densities.

The presence of the corrosion product (scab material) also attenuates the X-ray beam and hence affects the radiographic film density (and the grey levels seen on the digital radiographs). Localised spallation or cracking of the scab material will reduce X-ray attenuation, in a similar sense to localised loss of the substrate due to corrosion.

The motivation for identifying the presence of isolated fine pitting under scabs is that its presence may lead to significant undersizing of the wall loss when some NDT methods are used to determine the remaining ligament without removal of the scab material. Knowledge of

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the presence or absence of isolated pitting from double wall radiography could potentially be used to assess the likely uncertainty in the results from the other NDT methods.

There are limited examples of using the double wall single image technique to assess external corrosion scabs and it is not believed that the DWSI technique has been used in service to determine the presence of isolated pitting under external corrosion scabs.

However, this has been a topic in the recent HOIS trials which sought to determine whether this technique could detect the presence of isolated pitting under corrosion scabs, which may then affect the accuracy of other NDT methods that seek to measure minimum remaining ligament.

Note that in principle this method should also be applicable to double wall double image (DWDI) radiography of smaller diameter pipes.

A2.5.5.2 HOIS trial results

On behalf of HOIS, Bilfinger performed a series of preliminary tests to establish the potential for using double-wall single image radiography as a screening tool for determining the possible presence of isolated pits under external corrosion scabs [6].

For these trials, a number of ex-service external corrosion scabs were assessed. The pipes were well benchmarked, in that the morphology of the wall loss and minimum remaining ligament were known due to previously assessing them with an internal UT 'piglet' scanner developed by ESR Technology.

An example highlighting the correlation achieved between a photograph of the corrosion scab and the corresponding digital radiograph is shown in Figure A2-21. This digital radiograph was obtained with a Golden Engineering XRS3 pulsed X-ray unit (270 kVp). A flexible imaging plate (IP) was used (Waygate Technologies IPC2) which was in contact with the scab and curved around the pipe outside surface. The flexible imaging plate was read out using a Waygate Technologies CR25p scanner with a 100 µm pixel size.

Comparison of the two images in Figure A2-21 shows apparent correlation between the cracking and visible spallation on the scab surface and some of the features on the radiograph. Some examples have been highlighted in the figure.

This is to be expected because the presence of scab material attenuates the X-ray beam and hence affects the grey levels seen on the digital radiographs. In particular, localised spallation or cracking of the scab material will reduce X-ray attenuation, which will be shown as darker areas on the radiographs.

Note that localised loss of the substrate will also cause reduced X-ray attenuation and there is hence the potential for localised spallation of scab material to be incorrectly identified as wall loss in the substrate.

When compared with an internal UT scan previously performed on the scab, it is evident that the UT scan shows that seven of the dark circular features on the radiograph can be associated with areas of localised wall loss in the UT scan, including the deepest area of pitting shown at Location 4 (Figure A2-22). Regarding the colour pallet of the UT scan, black signifies the deepest area, followed by purple, blue, green, and finally red.

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If double wall radiography of external corrosion scabs were to be utilised in the field in this manner, the internal UT scans of the scabs would not be available. Therefore, a number of 3-D laser scans were performed on the scabs to establish the scab height and to allow for comparison with the radiographs.

An example of this comparison is shown in Figure A2-23 where the 2-D height map created from the laser scanning has been overlaid onto an image of the pipe. It must be noted that the colour scale of the laser scan height map shows white as the highest scab height, followed by red, green, blue, and finally purple. It is evident from the comparison that the deepest pit on the UT scan (Location 4) was approximately located under a comparatively high part of the scab material and that the circular regions in the radiograph at this location were not evident in the 2-D height map. This therefore suggests that the circular features at Location 4 were not a result of scab spallation and it could be reasonably assumed that these may be due to areas of wall loss when only referencing the visual scab image, radiograph, and the laser scan height map of the scab.

Another example (Figure A2-24) shows that the deepest pit on the UT scan (Location 2) is approximately located underneath what appears to be an area of scab spallation when compared with the 2-D height map. In practice, when the UT data is not available, it would be incorrect to assume that the dark region in the radiograph was solely a result of scab spallation when comparing the scab image, radiograph, and laser 2-D height map. It is therefore stressed that care must be taken when interpreting the results and it is recommended that other complementary NDT techniques also be used when performing on-site assessment of scabs.

Photogrammetry could potentially be used instead of laser scanning as a complementary method when interpreting DWRT radiographs of external corrosion scabs.

Given the limited size of this study, it is recommended that companies perform their own internal assessment to establish the reliability and accuracy of using this method for determining the presence of localised pitting underneath external corrosion scabs.

It is also important to note that if liquid product is present in the pipe when conducting radiography, the image contrast will be significantly reduced. The extent of the reduction will be dependent upon the level of liquid, the pipe diameter and wall thickness.

Note that in principle this method should also be applicable to double wall double image (DWDI) radiography of smaller diameter pipes.

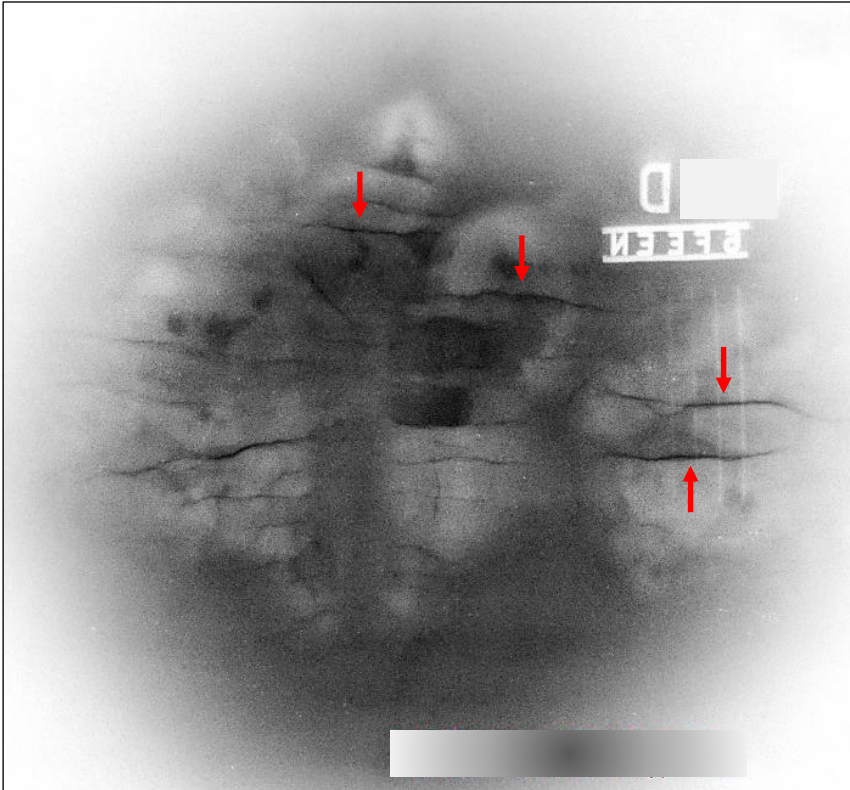


Figure A2-21: Example of an ex-service external corrosion scab and associated radiograph from the recent HOIS study

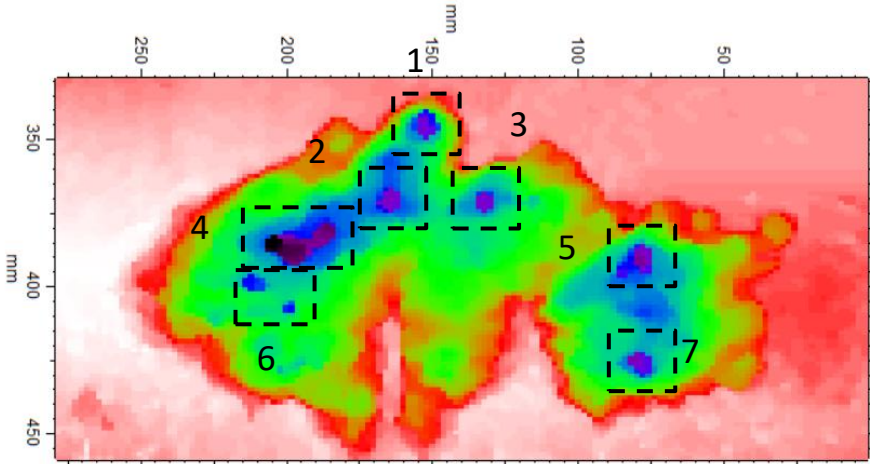
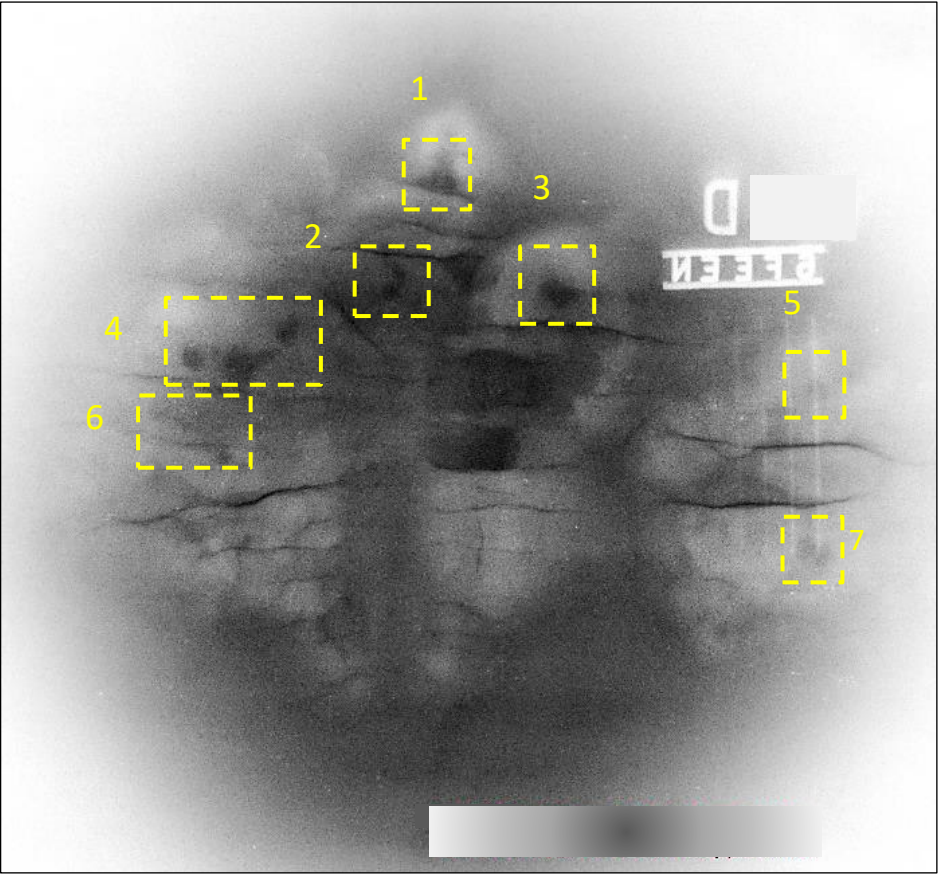


Figure A2-22: Comparison between a radiograph and a UT scan of a scab assessed in the recent HOIS study

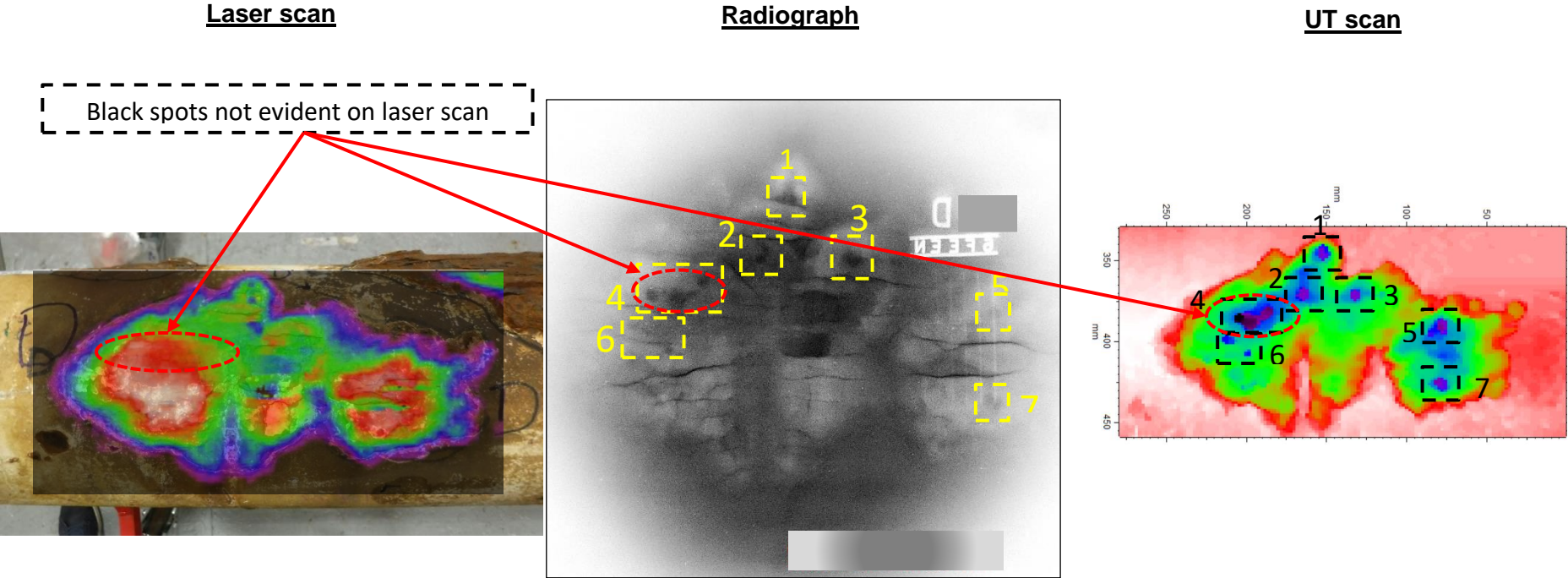


Figure A2-23: Comparison between radiograph, UT, and laser scan of a scab assessed in the recent HOIS study

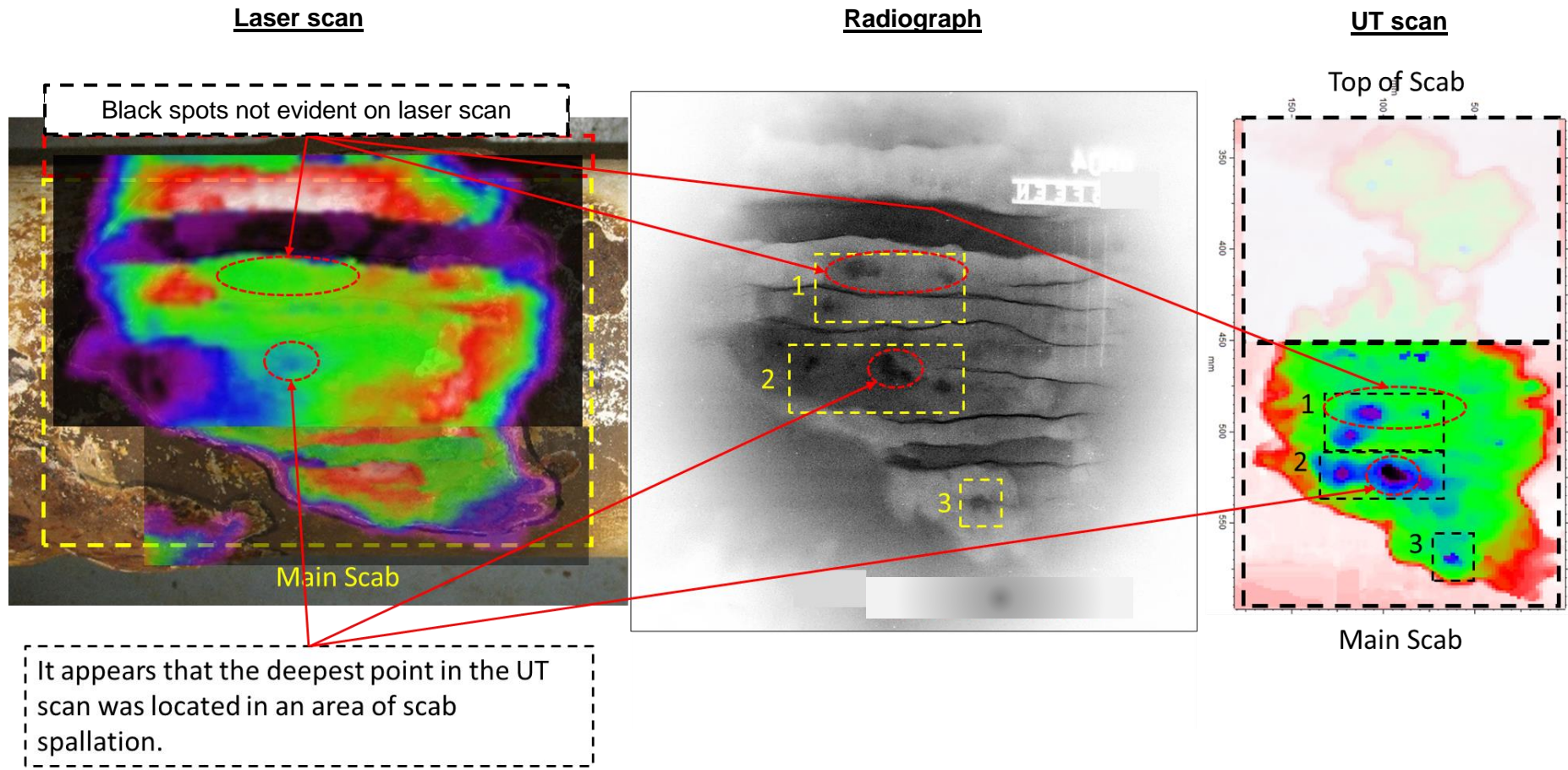


Figure A2-24: Comparison between radiograph, UT, and laser scan of a scab assessed in the recent HOIS study

A2.5.5.3 Summary

Method:	Double wall radiography to find localised corrosion pits by changes in image density/grey level using either film or imaging plate (IP/CR).
Basis:	Areas of localised corrosion can be seen on radiographs, even in the presence of corrosion product, although this reduces their contrast. A screening method to assess the scab for the presence of localised pitting which may affect the accuracy of other NDT methods for determination of minimum remaining ligament.
Strengths:	<ul style="list-style-type: none"> • Potential for use as a complementary method for determining the presence of isolated pitting under external corrosion scabs. • Radiographic image interpretation can be improved by reference to photographs of the scab, showing presence of any spallation of corrosion product. • 3-D laser scanning or photogrammetry can provide additional information on scab height morphology for improved radiographic image interpretation. • Applicable to wide range of complex geometries (bends, reducers etc.).
Limitations:	<ul style="list-style-type: none"> • A screening method for determining presence/absence of localised pitting only. • Does not provide a measure of wall loss or minimum remaining ligament. • Radiation safety issues. • Can be slow. • Not applicable to vessels. • Potentially affected by presence of liquid product which will reduce the image contrast.
Overall:	A screening method for determining presence/absence of localised pitting only which may affect the sizing accuracy of other NDT methods. No experience to date of field applicability but showed promise in limited HOIS trials on ex-service scabs with localised pits. Reliability of radiographic image interpretation improved by usage of photographs of scabs and 3-D height maps of the corrosion product from 3-D laser scanning or photogrammetry.



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