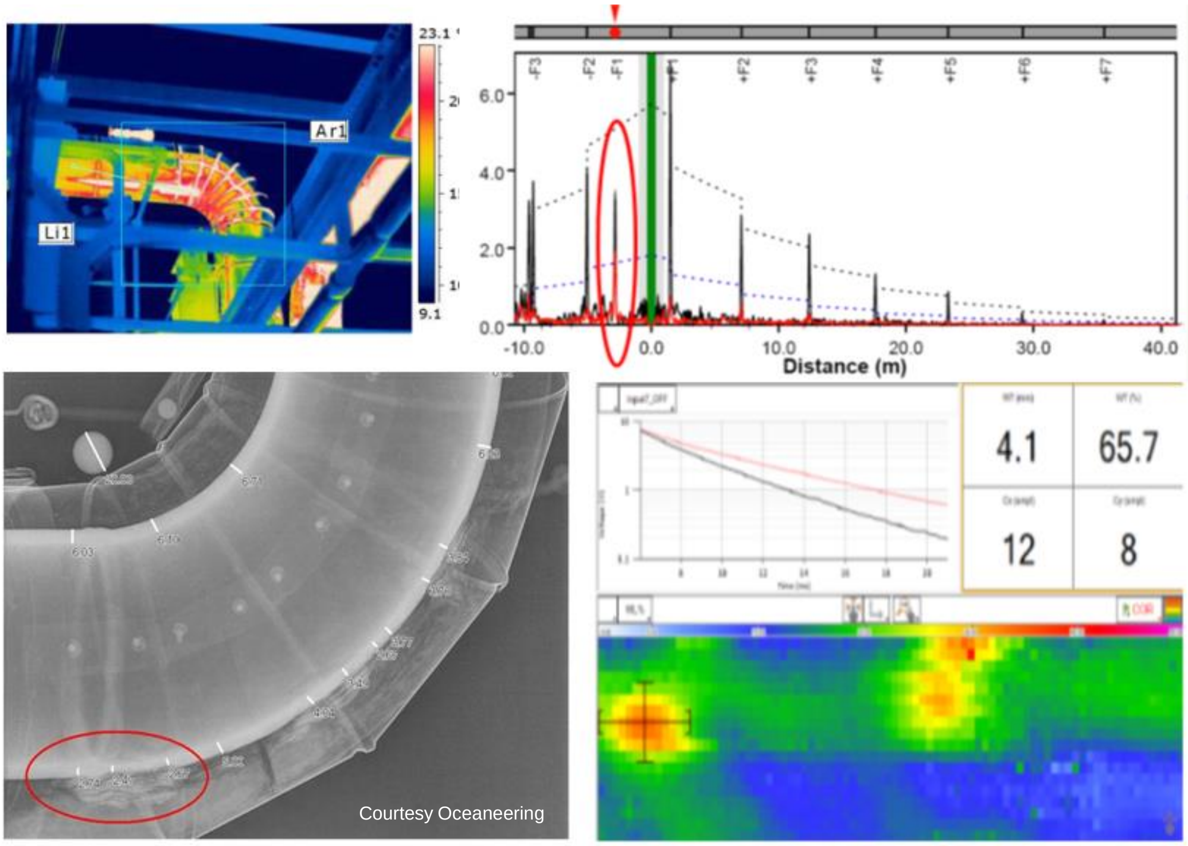

HOIS/OGTC Guidelines for in-situ inspection of corrosion under insulation (CUI)

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Executive Summary

Corrosion Under Insulation (CUI) is a major issue for oil and gas facility owners. Although CUI can be managed to some extent by use of improved coatings, insulation, cladding and installation, its occurrence is often unpredictable and there is a continuing interest in effective inspection/NDT methods to reduce the risk of loss of containment. There can also be a requirement to inspect equipment with known CUI to determine whether it is safe to remove the insulation from live lines.

Many asset owners currently rely on rolling programmes for removal of the insulation followed by visual inspection, fabric maintenance (if required) and then re-insulation without performing any routine NDT. This approach can be more reliable at locating CUI, which often occurs at changes in geometry (e.g. tees, branches, bends) where water ingress is more likely to occur, and NDT is often less reliable than on straight, uniform pipe sections. However, removal and reinstatement of insulation is a significant logistical exercise which in some cases requires either restricted operation or a plant shutdown. It is also time consuming, expensive, and the substrate can often be found to be in good condition. For some forms of insulation (especially passive fire protection) removal is difficult and may, itself, damage the substrate. As CUI is a widespread problem there remains strong interest in effective NDT methods for its inspection.

Many different NDT methods have been examined historically for this application. Ideally the NDT methods are required to reliably detect and accurately size the presence of CUI across a wide variety of components and geometries. However, the current experience with and track record of NDT methods is mixed. One of the main drivers for the initiation of this HOIS project is the perception that the industry awaits more effective NDT approaches, although there are some exceptions with reports of examples of effective NDT being applied in specific areas, with apparently successful results.

This document provides guidance on a wide range of current NDT methods available for CUI inspection, by detailing for each one their strengths, limitations and areas of applicability. This work should provide operators and NDT service providers with current relevant information on the best methods for this challenging application and lead to a more consistent approach across the industry.

Many factors need to be considered when assessing the applicability of an NDT method for CUI inspection including pipe (or vessel) OD, wall thickness, CUI morphology, the insulation material and thickness, as well as the outer cladding (or weather jacket) material and thickness.

It is important that any users of NDT for CUI are fully aware of the capabilities of the different methods available as these may make them suitable for application to a certain set of components under specified conditions, but not for general usage across a site. Clearly it is unrealistic to expect reliable results to be obtained if the methods are applied outside their range of applicability.

Although moisture detection (or indirect) methods for CUI inspection are covered in this document, they frequently appear to have limited effectiveness for reliable detection of CUI. This is primarily because wet insulation does not necessarily indicate the presence of CUI. CUI will not be present under wet insulation if the coating is in good condition, and CUI can be present under insulation that was dry at the time of inspection (having been previously wet). There can however be some value in application of an indirect method such as infra-red thermography as this can provide clear visualisation of wet areas of insulation which then promotes prompt removal of the insulation to assess the underlying condition of the substrate.

The NDT methods that are currently most widely applied for CUI inspection include guided wave testing (GWT), in both inspection and the more sensitive monitoring modes (e.g. gPIMS) and various radiographic methods. GWT is used extensively in a few geographical areas, mainly on long straight runs of above ground pipework and pipelines with limited attachments, bends and other geometry changes. When used as an inspection method, GWT does however have limitations for the detection of CUI that is circumferentially localised. When used as a monitoring tool, this limitation is less significant.

Conventional radiography using isotope sources and film, or increasingly digital detectors is used for sampling inspection of areas that are most likely to have CUI, particularly in small-bore pipework. Unlike GWT, it can be readily applied to features such as bends, tees and similar geometry changes. The slow throughput of conventional radiography is however a significant limitation.

Alternative radiographic approaches that are used successfully for CUI inspection include scanning systems based on digital detector arrays for inspection of long, straight runs of above ground pipework and pipelines with limited obstructions. In addition, handheld real-time imaging devices (e.g. OpenVision) are also widely used in certain geographic areas (e.g. USA) although their associated radiation hazards make them difficult to operate in compliance with the IRR17 in the UK.

Current technology development with potential for improved CUI inspection is mainly focussed on electromagnetic methods that may overcome some of the limitations of the traditional pulsed-eddy current methods that were originally developed for CUI. The Lyft system from Eddyfi provides faster data collection and the ability to continuously scan the component, although limitations due to insulation thickness/sensor footprint size remain. Other recently improved PEC systems include those from TUV Rheinland Sonovation and Maxwell NDT. The recent development of pulsed-eddy current arrays provides significantly enhanced coverage rates for straight pipes. Alternative approaches such as the Russell NDE Bracelet probe, and the prototype Exxam Systems MFECT equipment, gave encouraging results under certain conditions in the most recent HOIS/OGTC trials. Both systems are based on sensor arrays for increased coverage rates on straight pipes.

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1 Introduction

Corrosion Under Insulation (CUI) is a major issue for oil and gas facility owners. Although CUI can be managed to some extent by use of improved coatings, insulation, cladding and installation, its occurrence is often unpredictable and there is a continuing interest in effective inspection/NDT methods to reduce the risk of loss of containment. There can also be a requirement to inspect equipment with known CUI to determine whether it is safe to remove the insulation from live lines.

Many asset owners currently rely on rolling programmes for removal the insulation followed by visual inspection, fabric maintenance (if required) and then re-insulation without performing any routine NDT. This approach can be more reliable at locating CUI, which often occurs at changes in geometry (e.g. tees, branches, bends) where water ingress is more likely to occur, and NDT is often less reliable than on straight, uniform pipe sections. However, removal and reinstatement of insulation is a significant logistical exercise which in some cases requires either restricted operation or a plant shutdown. It is also time consuming, expensive, and the substrate can often be found to be in good condition. For some forms of insulation (especially passive fire protection) removal is difficult and may, itself, damage the substrate. As CUI is a widespread problem there remains strong interest in effective NDT methods for its inspection.

Many different NDT methods have been examined historically for this application. Ideally the NDT methods are required to reliably detect and accurately size the presence of CUI across a wide variety of components and geometries. However, the current experience with and track record of NDT methods is mixed. One of the main drivers for the initiation of this HOIS project is the perception that the industry awaits more effective NDT approaches, although there are some exceptions with reports of examples of effective NDT being applied in specific areas, with apparently successful results.

HOIS projects on CUI inspection commenced in 2012. An initial information gathering phase (Burch, 2013) identified a provisional short list of five NDT methods that were considered sufficiently promising for further investigation by means of trials, where possible, and discussions with experts in the corresponding technology.

A trial programme was then conducted, managed by ESR Technology, which comprised both site trials and those in the NICE facility. A variety of different samples and components were examined using five short listed methods and the results obtained were described by Burch and Kitchener (2016).

A further major trial-based project was started in 2017, with co-funding from the Oil & Gas Technology Centre (OGTC) which enable the scope to be expanded and timescale accelerated. Eleven trials of electromagnetic NDT methods for CUI were conducted at the HOIS NICE facility, on a set of manufactured 10” pipes containing areas of simulated corrosion generated using advanced CNC machining methods to obtain morphologies representative of examples of service induced external corrosion. In addition, trials using radiographic methods and PEC were conducted on some ex-service small-bore pipes. The results obtained in these trials were described in a comprehensive trial report (Burch and Collett, 2019).

The present document provides guidance on the inspection of CUI, based on these trial results, where available, and other information obtained during these HOIS projects. This document gives, in Section 3 and Appendix 1, a summary of relevant information on CUI within the oil and gas industry. The main methods currently available for NDT of corrosion under insulation are summarised in Section 4 and Appendix 2. Where available, performance and reliability information obtained from the HOIS CUI trials is given. Developmental methods are considered in Section 5 and Appendix 3. Section 6 gives further information on the CUI NDT trials while Section 7 provides guidance on application of the methods depending on the inspection requirements, including summary tables of method applicability. Usage of NDT within a strategy for CUI integrity management is considered in Section 8, which also includes some case studies, provided by HOIS members, involving successful application of NDT for CUI inspection.

2 Terms and Abbreviations

A	Aspect ratio of an area of wall loss, defined by its average axial and circumferential extent, divided by its maximum wall loss.
a50	Term used in POD analysis. The dimension giving a POD of 0.5 for a curve fitted to the hit/miss values plotted as a function of the dimension, e.g. maximum wall loss in mm or %WT
a90	The dimension giving a POD of 0.9 for a curve fitted to the hit/miss values plotted as a function of the dimension, e.g. maximum wall loss in mm or %WT
a90/95	The dimension giving a lower bound POD of 0.9 with a confidence of 95% for a curve fitted to the hit/miss values plotted as a function of the dimension, e.g. maximum wall loss in mm or %WT
AWT	Average wall thickness. Term mainly applied to remaining wall thickness values measured using PEC. The average is a spatial average over the sensor footprint area.
CS	Carbon steel
CWT	Compensated wall thickness. Term used by Eddyfi for remaining wall thickness values measured using Lyft. The compensation is for localised areas of wall loss and is intended to reduce the spatial averaging over the sensor footprint area that occurs with this method
DDA	Digital detector array. Term used for digital radiography.
DWDI	Double wall double image. A term used in radiography involving use of a radiation source separated from the pipe under inspection such that the radiographic image shows detail in both the pipe walls, including the one on the source side.
DWT	Defect wall thickness. Term used by TUV Rheinland Sonovation applied to remaining wall thickness values measured using Sonopec. The defect wall thickness is intended to be more accurate than AWT for localised areas of wall loss by reducing the spatial averaging over the sensor footprint area that occurs with this method
E	Average of the circumferential and axial extents of an area of wall loss
EM	Electromagnetic
f or fill factor	Volume fill factor. The volume of an area of wall loss divided by the corresponding volume of a flat-bottom hole with height w and diameter E.
GMR	Giant Magnetoresistance (sensors) – used as the basis for a CUI inspection method, developed by the Robinson Research Institute, New Zealand
GWT	Guided Wave Testing
IRR17	The Ionising Radiations Regulations 2017, HSE, UK Statutory Instruments 2017 No. 1075
IS	Intrinsic safety. Needed for monitoring equipment installed in a hazardous environment.
MDI	Moisture detection imaging (MDI) – equipment developed by Acuren, USA
MFECT	Multi Frequency Eddy Current
PEC	Pulsed Eddy Current
POD	Probability of detection
SS	Stainless steel
TRL	Technology Readiness Level (1-9) on the NASA scale – see https://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html
V	Volume of the missing material in an area of wall loss
w	Maximum wall loss

WT	Uncorroded wall thickness, generally measured locally to each area of wall loss. Manufacturing tolerances cause WT to differ slightly from the nominal pipe wall thickness
σ	Standard deviation of a set of values

3 CUI in the oil and gas industry

There are a number of significant publications that detail the corrosion mechanisms and other factors that lead to corrosion under insulation, and also cover aspects of CUI integrity management (e.g. Winnik, 2008; API 571; API 583). However for completeness, the main aspects and key points of CUI within the oil and gas industry are summarised in Appendix 1, which is largely based on the Phase 1 report (Burch, 2013), updated where appropriate.

4 NDT Methods currently available for CUI inspection without insulation removal

NDT methods that are fully developed (TRL 8-9) and have been deployed on-site for applications including CUI inspection are detailed in Appendix 2.

5 Developmental methods for CUI inspection

In addition to the current NDT methods described in Appendix 2, CUI inspection is an area that has attracted considerable amounts of research. This has resulted in various developmental approaches that are summarised in Appendix 3.

6 Trials of NDT Methods for CUI inspection

Within the HOIS JIP there have been two sets of trials of NDT methods for CUI inspection. The first set of trials took place between 2014 and 2015 (Burch and Kitchener, 2016). Although most of the trials were based on ex-service components in the HOIS NICE facility, some were site trials. The following NDT methods were included in this set of trials:

1. Pulsed Eddy Current (NICE facility trial)
2. Guided Wave Testing (NICE facility trial, site trial)
3. Advanced electromagnetic - Bracelet Probe (NICE facility trial).
4. Real time radiography (OpenVision trial at Oceaneering, Aberdeen)
5. DDA radiography (in combination with a flash X-ray source - site trial)
6. Passive infrared thermography (site trial).

As part of the current HOIS/OGTC project on CUI and scab NDT, a further set of trials took place, mainly on manufactured pipes into which areas of wall loss representative of service induced corrosion were introduced using an advanced CNC machining process (Burch and Collett, 2019). Further trials were performed on ex-service small-bore pipes with external corrosion scabs. The following methods were included in this second set of trials:

- PEC (Lyft, Sonopec and PECT)
- Bracelet Probe

- MFECT
- GMR eddy current
- Real-time radiography - Open Vision
- Digital Radiography

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

7 Guidance on selection of NDT methods for CUI inspection

Detailed information is given on all the currently used NDT methods for CUI inspection in Appendix 2.

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

- Is it possible to perform a limited removal/penetration of the insulation?
- Is access possible to the insulated component or does this make the inspection prohibitively expensive?
- Radiation hazards - can they be adequately managed?
- Is there a temperature differential between the pipe and ambient?
- Is direct detection of CUI needed, or is indirect information (moisture in the insulation) adequate?
- Does the method need to provide quantitative measurement of remaining ligament?
- Does the method need to be applicable to vessels?
- Does the inspection need to cover geometry changes (tees, supports, connections etc.)?
- Is the corrosion product likely to remain in-situ on top of the area of wall loss?
- Does the pipe diameter and wall thickness meet the method limitations?
- Is the insulation thickness within the capability of the method?
- Is there a need for detection of CUI through wet insulation?
- Does the cladding material, cladding thickness and any cladding overlap create limitations for the method?
- Does the available information on the sensitivity of the method to CUI match the requirements of the inspection? Note that the sensitivity of many methods to wall loss also depends on the axial and/or circumferential extent of the corrosion. Corrosion with small axial and circumferential extents is usually more difficult to detect than wall loss that is extended over a larger area.

Table 7.1 gives a summary of the information contained in Appendix 2 in a format that allows the factors listed above to be considered for all methods.

Table 7.2 and Table 7.3 give a simple summary of overall CUI inspection capabilities by method, using a traffic light system to indicate applicability/limitations as follows:

Green	No significant limitations
Orange	Some limitations.
Red	Marginal or no applicability

It is important to note that each NDT method should only be applied within its known area of capability, taking account of the limitations identified in Table 7.1 and the simpler summaries given in Table 7.2 and Table 7.3. If a method appears to be applicable to a particular component on the basis of this table, it is then important to also check its suitability given the more detailed information contained in Appendix 2.

Table 7.1: Summary of current developed methods for CUI inspection (TRL 8 or 9)

	Moisture detection methods (indirect)				Direct inspection for CUI							
	Water collectors	Passive infra-red thermography	Neutron Backscatter (Hydrotector)	Moisture Detection Imaging (MDI)	GWT	Tangential radiography	Tangential radiography without full penetration of pipe wall	Double-wall single image radiography	Real-time imaging radiography (e.g. OpenVision)	Real-time profile radiography (e.g. LIXI)	Pulsed eddy current*	Russell NDE Bracelet probe
Limited removal/penetration of insulation needed?	Y	N	N	N	Y	N	N	N	N	N	N	N
Direct access needed to insulated component	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Radiation hazards	N	N	Y	Y	N	Y	Y	Y	Y[1]	Y	N	N
Temperature differential required between pipe and ambient	N	Y[2]	N	N	N	N	N	N	N	N	N	N
Direct detection of CUI	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y
Fast screening	N	Y	N	Y	Y	N	N	N	N	N	N[3]	N[3]
Quantitative measurement of remaining ligament	N	N	N	N	N	Y[4]	N	N	N	N	Y[5]	N
Applicable to vessels	Y	Y	Y	Y	N	N	N	In special cases	N	N	Y	Y
Applicable to geometry changes (tees, supports, connections etc.)	Y	Y	Y	Y	Some applicability to bends & supports	Y	Y	Y	Y	Y	Y[14]	N
Corrosion product effects	N	N	N	N	N	N	N	Y[6]	N	Y[6]	N	N
Pipe diameter limitations	N	N	N	N	≥ 3/4" < 60" (up to 72" by combining rings)	Note 7	N	Note 8	~20"	~0.5 to 24"	≥1"	>4" with 25mm insulation
Pipe wall thickness limits	N	N	N	N	4mm to ~70mm	Note 7	N	≤ 50mm for Ir 192[8]	N	15mm[9]	≤100mm	N
Maximum insulation thickness (mm)	N	N	N	N	N	N	N	N	N	N	≤300mm	~100mm
Detection of CUI through wet insulation	Detects wet insulation not CUI				Y	Y	Y	Y	Not proven	Will increase apparent wall thickness	Y	Y
Cladding material and thickness limitations	N	Low emissivity issues with shiny metallic claddings	N	N	N	N	N	N	N	N	Note 10	Conducting cladding OK. Not ferromagnetic
Cladding overlap limitations	N	N	N	N	N	N	N	N	N	N	N	Not proven
CUI detection limit/POD info	N	N	N	N	Y[11]	N	N	N	N	N	Y[15]	Y[15]

Footnotes

*	Based on Eddyfi Lyft information
1	Issue with operation in UK to IRR 2017. Perceived to be less of an issue in some other countries (e.g. USA).
2	Infra-red thermography requires a temperature differential of at least 10°C according to API 583.
3	These electromagnetic methods achieve appreciably higher coverage rates than conventional pulsed eddy currents.
4	Tangential radiography can accurately size the remaining ligament under some areas of CUI but may significantly undersize others, depending on the corrosion morphology (Burch, 2014).
5	Pulsed Eddy Current methods measure the remaining wall thickness averaged over the sensor footprint. This may underestimate the severity of the CUI if it extends, or varies in depth, over an area smaller than sensor footprint.
6	Corrosion product in place over the CUI will attenuate the radiation by a similar amount to uncorroded steel and will significantly affect the detectability of the CUI and make any measurements of wall loss unreliable. Some corrosion product may even have the effect of making the apparent steel wall thickness higher than the uncorroded value.
7	For tangential radiography the limiting factor for the radiation source in use is the maximum tangential path which depends on the wall thickness and pipe diameter (see equation 3.1).
8	The total steel equivalent penetrated thickness when using Ir 192 is ~ 100mm, which includes any contribution due to liquid product and insulation (see EN16407:2).
9	For the Lixi profiler, the total steel equivalent penetrated thickness is ~ 30mm, which includes any contribution due to liquid product and insulation (wet or dry).
10	Pulsed eddy current methods are applicable to non-metallic cladding materials and conducting metallic claddings (e.g. stainless steel, aluminium). Ferromagnetic cladding materials (e.g. galvanised steel, Aluzinc) reduce the effectiveness and enlarge the sensor footprint.
11	GWT is sensitive to loss of pipe wall cross-sectional area (CSC). In inspection mode, the detection limit is ~5%. In monitoring mode (gPIMS) the detection limit is ~1%. The relation between these values and wall loss depends on the circumferential extent and profile of the CUI (see Appendix A2.7 for more information).
12	From HOIS/OGTC trials on 10” sch 20 pipes with areas of CUI having an average aspect ratio (lateral extent/depth) of ~45. Different results are likely on pipes with different wall thickness, diameter and CUI characteristics.
13	According to Dedenberg et al (2015), for 6.4mm wall thickness pipes with 50 mm of insulation and 0.51 mm thick aluminium cladding, the detectability of CUI (weather jacket) depended on the diameter of the CUI. For 25mm diameter, the minimum detectable wall loss was 65%. For 76mm diameter, the minimum detectable wall loss was 30% (see Section 0 for more details).
14	Capabilities to scan elbows, mass effect algorithm to minimize supports and other altering components
15	These methods were included in the HOIS CUI POD trials and the full results obtained are given in Burch and Collett (2019). See also the trial summary information given in Appendix 2.

Table 7.2: Summary of CUI inspection applicability by method (part 1)

	Can't remove any insulation or cladding	Can't access the component directly	Radiation hazards	Direct detection of CUI needed	In routine usage for CUI inspection	Quantitative measurement of remaining ligament	Straight pipe	Bends	Tees, supports and other geometry changes
Water collectors	Orange	Red	Green	Red	Green	Red	Green	Green	Orange
Passive infra-red thermography	Green	Green	Green	Red	Orange	Red	Green	Green	Green
Moisture detection imaging	Green	Red	Red	Red	Orange	Red	Green	Green	Orange
Neutron Backscatter (Hydrotector)	Green	Red	Red	Red	Orange	Red	Green	Green	Red
GWT	Red	Red	Green	Green	Green	Red	Green	Orange	Red
Tangential radiography	Green	Red	Red	Green	Green	Orange	Green	Green	Green
Tangential radiography without full penetration of pipe wall	Green	Red	Red	Green	Orange	Red	Green	Green	Green
Double-wall single image radiography	Green	Red	Red	Green	Red	Red	Green	Red	Red
Real-time imaging radiography (e.g. OpenVision)	Green	Red	Red	Green	Orange	Red	Green	Green	Green
Real-time profile radiography (e.g. LIXI)	Green	Red	Orange	Green	Orange	Orange	Green	Green	Red
Pulsed eddy current	Green	Red	Green	Green	Orange	Orange	Green	Orange	Red
Russell NDE Bracelet probe	Green	Red	Green	Green	Orange	Red	Green	Orange	Red

Key to colours used above:

Green No significant limitations
Orange Some limitations.
Red Marginal or no applicability

Table 7.3: Summary of CUI inspection applicability by method (part 2)

	Small bore pipes	Larger diameter pipes	Vessels	Ferromagnetic cladding or material in insulation	Insulation up to 50mm	Insulation between 50 & 75mm	Insulation Between 75 & 100mm	Insulation > 100mm
Water collectors	Green	Green	Green	Green	Green	Green	Green	Green
Passive infra-red thermography	Green	Green	Green	Orange	Green	Green	Green	Green
Moisture Detection imaging	Green	Green	Green	Green	Green	Green	Green	Green
Neutron Backscatter (Hydrotector)	Green	Green	Green	Green	Green	Green	Green	Green
GWT	Orange	Green	Red	Green	Green	Green	Green	Green
Tangential radiography	Green	Red	Red	Green	Green	Green	Green	Green
Tangential radiography without full penetration of pipe wall	Green	Green	Red	Green	Green	Green	Green	Green
Double-wall single image radiography	Green	Green	Orange	Green	Green	Green	Green	Green
Real-time imaging radiography (e.g. OpenVision)	Green	Orange	Red	Green	Green	Green	Green	Green
Real-time profile radiography (e.g. LIXI)	Green	Orange	Red	Green	Green	Green	Green	Green
Pulsed eddy current	Orange	Green	Green	Orange	Green	Green	Green	Orange
Russell NDE Bracelet probe	Orange	Green	Green	Red	Green	Green	Green	Red
Jentek MWM	Orange	Green	Green	Red	Green	Green	Red	Red

Key to colours used above:

Green No significant limitations
Orange Some limitations.
Red Marginal or no applicability

8 Usage of NDT as part of CUI integrity management

8.1 Introduction

Despite many years of NDT technology development, it is generally perceived that there is no silver bullet for CUI inspection, and the industry awaits a reliable and effective NDT method capable of widespread application across a broad range of plants and components.

Through a recent CUI Joint Industry Project (JIP), DNV GL has, together with partners from the oil and gas industry, established a methodology for managing the CUI threat. In this context, managing the CUI threat involves risk assessment, risk mitigation and risk update in a systematic manner (DNVGL-RP-G109). In addition to many other factors and issues, this RP considers the usage of NDT as part of the CUI integrity management process.

A detailed consideration of the CUI integrity management process is beyond the scope of the present document. However, some information is given below on economic considerations for including NDT in the integrity management process (Section 8.2). Also, some examples are given in Section 8.3 of apparently successful field applications of NDT methods for CUI inspection. Section 8.4 gives further examples of successful applications of NDT for CUI in the form of case studies provided by cat 2 HOIS members.

8.2 Application considerations

8.2.1 Background

Before applying NDT methods to inspect for CUI, it is generally necessary to consider the costs of applying the NDT, compared with the alternative of insulation removal which would then be followed by fabric maintenance and then reinstatement of the insulation.

The relative costs of NDT and insulation removal vary widely from one application to another, and so it is not possible to give general guidelines here.

The following costs and factors should however be considered before using NDT as an alternative to insulation removal and replacement:

8.2.2 Cost of insulation removal, surface preparation and re-insulation

Many asset owners seek to manage CUI by means of extensive rolling programmes of insulation removal, surface preparation/fabric maintenance to remove any corrosion found and then re-insulation.

Costs for this process depend on many factors, including

- Replacement of insulation
- Refurbishment of surface
- Scaffolding
- Pipe function, diameter, complexity (valves, flanges, elbows), access, condition, temperature etc.

The table below, adapted to GBP from Ryen (2019), gives approximate total costs for removal and replacement of insulation, for offshore installations in the Norwegian sector of the North Sea (average complexity).

Table 8.1: Approximate total costs for insulation removal, surface preparation and re-insulation (adapted from Ryen, 2019).

Pipe NB	Total cost per 10m pipe section (£k, 2017)
2”	6 - 10
8”	8 – 20
18”	17 - 60

Given the amount of insulated pipework in the industry, the total costs of these programmes are very high. For example, one Norwegian operator has 5000km of insulated pipes on its plants in Norway. Combining this total with the figures given in the table above, shows that the total cost to this operator for replacing all 5000km of insulation would be of order £10 billion, assuming a mid-range cost of £20k per 10m section.

In many cases, removing the insulation may show that the component is in good condition and free from coating breakdown and CUI. Hence the removal of the insulation was not required.

Despite the large amounts spent on this process, leaks due to CUI still occur, often in unexpected locations.

8.2.3 Scaffolding

If scaffolding is needed to provide access for performing NDT, this can amount to 80% of the total cost of insulation removal, surface preparation and re-insulation.

This can then make it difficult to support an economic case for NDT. Hence the most likely economic applications for NDT will not involve scaffolding.

New deployment technologies (e.g. robots, crawlers, drones) for NDT methods for CUI would be one way of improving the economic case for NDT in these circumstances.

8.2.4 Coating Breakdown/failure

As stated in Appendix 1, CUI does not occur while the external coating is intact. Once this has failed, corrosion can be rapid. Coating failure tends to be localised and its distribution is not entirely random as welds, due to their uneven surface, are more prone to coating defects. However, when covered by insulation, it is often not possible to identify weld locations except at flanges, attachment welds and branch connections.

At present, there are no NDT methods capable of checking coating condition and there is no information of any active R&D in this area.

Existing NDT methods fall into two categories, moisture detectors, which give an indication only of the integrity of the weather shield, and those which detect loss of material. The former will not detect either CUI or coating failure; the latter will only detect CUI once there has been a significant material loss and therefore could give false confidence where a coating is beginning to fail.

8.2.5 NDT cost and coverage

The cost of performing NDT depends largely on its speed of application. Some methods such as GWT (see Appendix A2.5) can screen long lengths of pipe from one inspection location (the full pipe circumference up to 100m in both directions in favourable circumstances; range can be significantly reduced by various factors including coating type, presence of flanges) and are hence relatively inexpensive to apply when considered in terms of the length and surface area of pipe inspected.

Other methods, that involve scanning of the insulated and clad pipe surface directly above any possible CUI will be much slower and hence more costly. If the inspection is limited to the 6 o'clock position then the time required per metre of pipe will be less, but the risk is that any corrosion away from the 6 o'clock position will be missed.

Achieving full 100% coverage of a component may require a combination of NDT methods. Many NDT methods are applicable only to straight sections of pipes or vessels, and cannot be applied to regions of more complex geometry, which can include elbows, tees, pipe supports, branch connections etc.

It is often these areas that are more prone to water ingress, coating breakdown and hence CUI. More specialised, slower and potentially less effective NDT methods may be needed to inspect these complex geometry sections.

The extent of coverage achieved will have an effect on the overall probability of detection of CUI. Even if a high POD is achieved on straight pipe sections, then it is important to consider that the overall POD will be substantially lower unless all sections of the component have been inspected, including those with more complex geometries which may be more prone to CUI.

8.2.6 NDT sensitivity and probability of detection

All NDT methods will fail to identify corroded areas that are below their detection limits. The probability of detection (POD) is never one, so there is always a risk that some corrosion will be present even if NDT has been applied, and no significant indications are reported.

As shown in the HOIS/OGTC CUI NDT trials (Burch and Collett, 2019), the POD of an NDT method is dependent on many factors including:

1. The NDT method
2. The pipe diameter and wall thickness
3. The insulation thickness (and sometime type of insulation)
4. The thickness and type of cladding.
5. The maximum wall loss of the corrosion, and its extents in the axial and circumferential directions. The shapes of the axial and circumferential profiles of the wall loss due to the corrosion can also be important (some NDT methods are sensitive to the volume of missing material within their sensor footprints).
6. Complex geometries. Elbows, tees and other features are usually more difficult to inspect for CUI, and also tend to be high risk locations for CUI, due to possible moisture ingress at any cladding penetrations. Radiography of small-bore pipes is an exception in that it is applicable to most geometries, as well as straight pipes.

Even for straight pipes, there is no single POD value for any one NDT method. All NDT methods will have a low POD for small areas of corrosion and a higher POD for larger areas. The POD will also be affected by the other factors listed above.

The HOIS/OGTC CUI trials (Burch, 2019) showed that for a set of electromagnetic NDT methods for CUI detection and sizing, the following conditions gave the highest POD values in terms of percentage of wall thickness:

- Stainless steel cladding not galvanised. (Aluminium cladding likely to give similar results to stainless steel).
- No chicken wire in the insulation
- 50mm insulation not 100mm insulation.
- Sch 80 (15mm nominal WT) not sch 20 (6.4mm nominal WT).

Given these conditions, the two best performing methods gave 50% POD for areas of corrosion with wall losses of 12%, and all but one of the other methods gave 50% POD for wall losses of 20% or less. Higher PODs were obtained for larger areas of wall loss.

Note however that these figures are specific to the morphologies of the corroded areas included in these trials. For electromagnetic methods, the volume of the corrosion is likely to be a more universal measure of sensitivity. In these trials, 50% POD was obtained for a wide range of volumes, depending on the NDT methods and the trial variables given above. However, for the sch 80 pipes, the two best performing methods gave 50% POD for wall loss volumes of ~1ml, while for the sch 20 pipes, the best performing method gave 50% POD for ~2ml. Again, higher PODs were obtained for larger volumes of wall loss.

8.2.7 Likelihood of CUI being present

The likelihood that there is CUI present at a level sufficient to be detected by the proposed NDT should be considered. If there is a high probability of corrosion being present, there may be little economic benefit from applying NDT, as stripping of the insulation will be needed anyway for confirmation. Hence the cost of the NDT will then be additional to the cost of the insulation stripping, surface preparation and re-insulation.

8.2.8 Scheduling of the inspection

Unlike insulation removal, NDT can usually be applied to live lines, without waiting for a shutdown. In some cases, the ability to schedule NDT without needing to wait for a scheduled shutdown may be an important factor in favour of performing NDT.

8.3 Examples of successful usage of routine NDT for CUI

NDT is being used for CUI inspection in certain niche areas in the industry and is considered by those involved to be giving valuable and cost-effective results. During the course of this HOIS project information has been obtained on the following examples of routine usage of NDT for CUI detection:

- GWT for inspection and monitoring of long, generally straight above ground pipes and pipelines with few junctions. In one area of the Arctic alone a few years ago, Mistras were typically taking 3000 standard shots a year using conventional removable GWT rings and 4 shots per year from 500+ gPIMS devices, which are mainly installed on road crossings through culverts where insulation is also present on the pipe. The standard shots cover inspection of more than 50km of pipe for CUI each year.

Corrosion at pipe supports and other locations (e.g. welds) can also be found using GWT. Monitoring provides greater sensitivity to corrosion, especially at locations that generate GWT signals (welds, supports). See also the case studies in Section 8.4.1.

- Scanning systems based on real-time tangential radiography with digital detector arrays (DDA) are reported to be also used in an area of the Arctic for CUI inspection of long, generally straight above ground pipes and pipelines with few junctions, although information on this application is limited.

- Usage in the USA and some other geographical areas (but not to date the UK) of the hand-held OpenVision real-time radiographic device for routine scanning of pipework for CUI, generally at the 6 o'clock position.

- Tangential radiography using film, imaging plates or DDA's for sampling/follow-up inspections mainly of small-bore pipes, particularly at bends and other geometry changes which may be susceptible to CUI.

- Successful deployment of pulsed-eddy current technology to locate CUI under insulation and passive fire protection in an off-shore location (see Section 8.4.2).

8.4 Case studies

8.4.1 Guided Wave Testing (GWT)

These case studies were provided by GUL (Wavemaker) and Eddyfi (Teletest® Focus+).

8.4.1.1 Case study 1 - CUI / Corrosion at welded support

This case study involved a 4" NB pipeline with a Zinc coated pipe surface and mineral wool insulation. The requirement of the inspection included inspection of the longitudinal welded pipe supports for CUI. The insulation was removed at the inspection location and a 4" Solid sensor ring was installed, as shown in Figure 8-1. This was connected to a GUL WaveMaker® G4-mini instrument and readings obtained.

Figure 8-1: Test location for inspection of 4" pipeline.

The GWT data from this test location showed a significant indication at about -3m from the sensor ring, centred approximately at the 6 o'clock position (see Figure 8-2). The characteristics of this response from the support region indicated the presence of CUI. After removal of the insulation, this was confirmed to be due to severe corrosion at the welded support (see Figure 8-2, left).

In this case, the GWT response from this support was stronger and had different characteristics from those from other similar supports with no corrosion (i.e. multiple echoes at different axial positions along the support). In Figure 8-2, the other welded support to the right (at a distance of ~+1m from the sensor) shows a more typical, weaker response. Using reference supports is always useful, as the GWT responses from uncorroded supports can be highly variable, depending on the type of support, whether or not it is welded, etc.

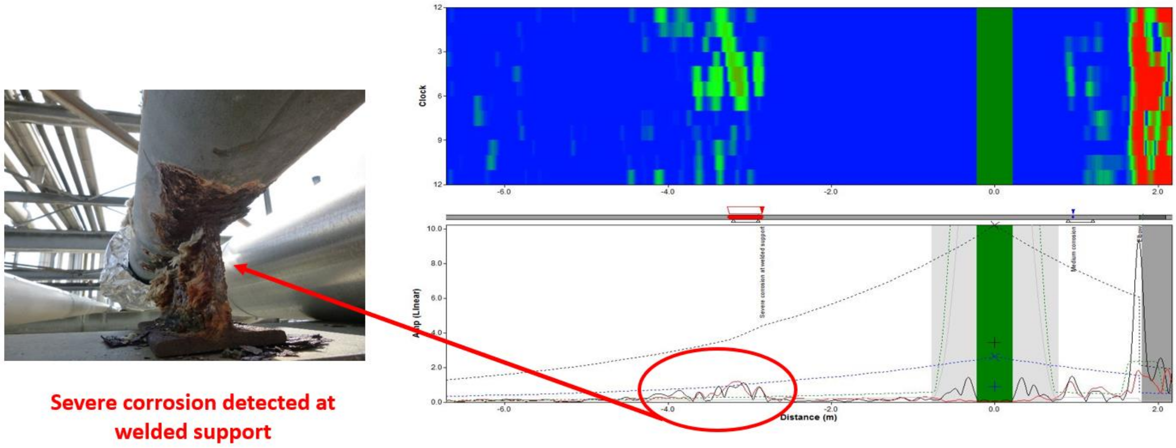

Figure 8-2: GWT data (right) and corresponding corrosion found at the support (left), after removal of the insulation.

In this case study, the GWT screening of the pipeline enabled the detection of a strong indication at a welded support. The indication was visually confirmed as severe corrosion damage at the welded support following the removal of the insulation.

8.4.1.2 Case study 2 – CUI on a cross-country flowline

This case study involved a 16" cross-country flowline with polyurethane foam Insulation. The insulated pipe was resting on simple supports so that there was no metal to metal contact at the supports. Hence the support locations did not generate strong GWT responses.

The aim was to detect any CUI present. GWT was used as the primary inspection method for this pipeline. 33 test positions were used to screen a total length of 740m of the pipeline (an average of 22m per test position). UT/RT was used as the secondary inspection method to follow-up the indication locations marked by GUL Screening.

The equipment used comprised a WaveMaker® G4 with a 16" EFC inflatable sensor ring.

A number of significant indications, well above the reporting threshold, were found. In total, 17.7 m of minor corrosion, 3.6 m of medium corrosion and 0.9 m of severe corrosion was found. In this flowline, the CUI was found to be close to or at a weld, as this was where the joins between factory and field applied insulation were. Corrosion on the weld itself will tend to reduce its amplitude.

An example of a location confirmed to have medium corrosion following removal of the insulation is shown in Figure 8-3.

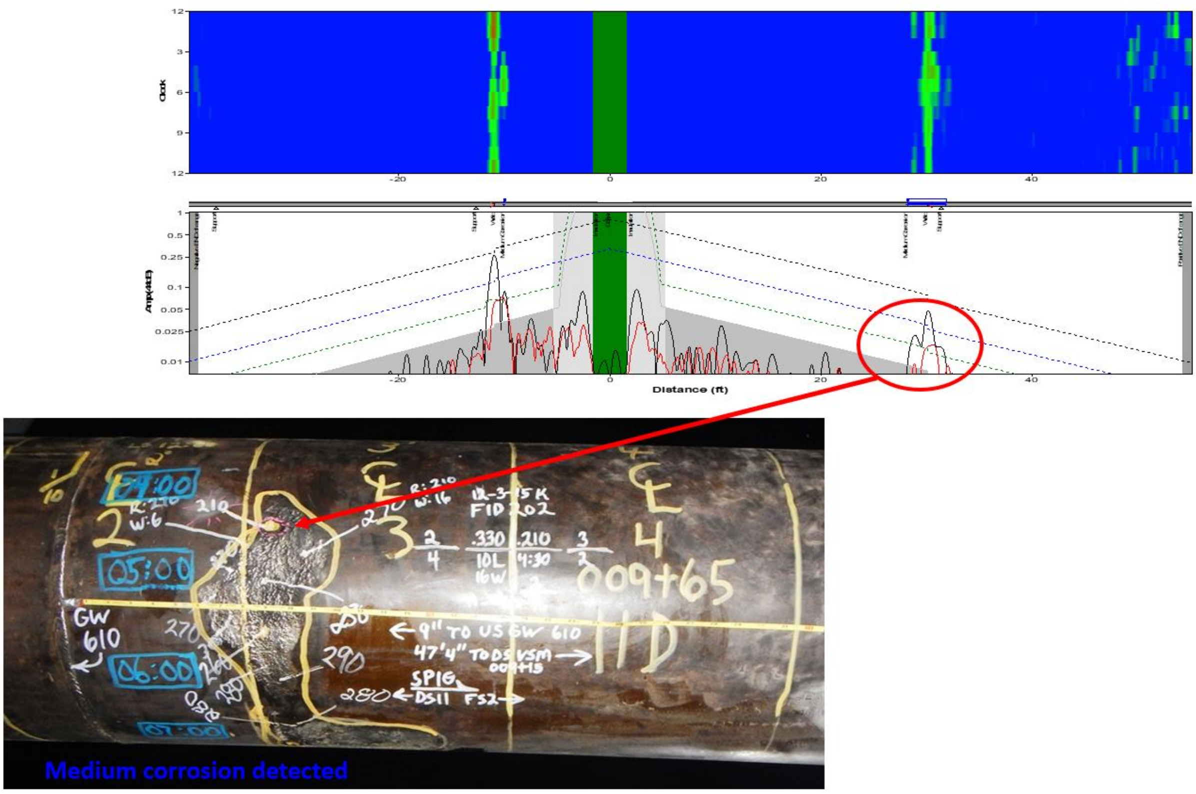

Figure 8-3: GWT data (top) and corresponding area of CUI (bottom), confirmed after removal of the insulation.

After insulation removal, the indication was followed-up with external UT and the minimum remaining wall thickness was found to be 5.3mm, with an uncorroded wall thickness of 8.4mm (37% wall loss). The axial length of the corroded area was 250mm and the circumferential extent was 400mm.

The follow up on the other indication found at this inspection location is shown in Figure 8-4. This again showed a medium level of corrosion, with a minimum remaining ligament of 4.6mm (45% wall loss) which was extended over an axial length of 790mm and 1100mm in the circumferential direction.

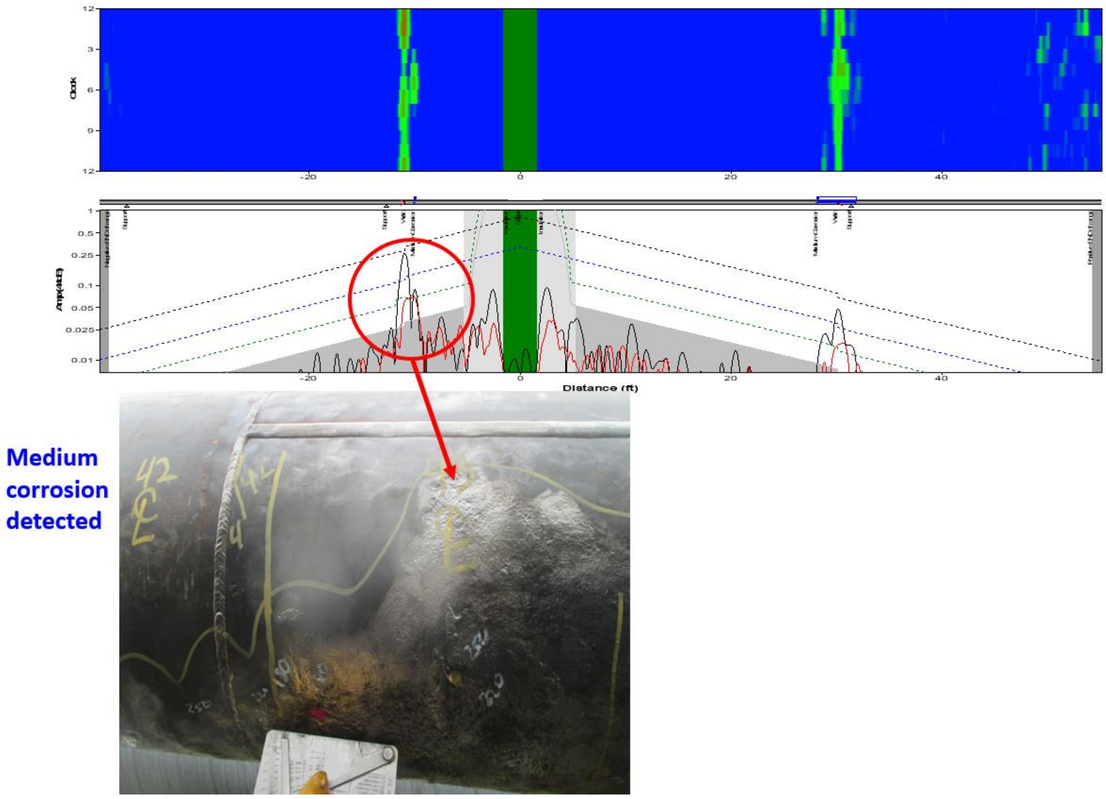

Figure 8-4: GWT data (top) and corresponding area of CUI (bottom), confirmed after removal of the insulation.

A location identified as having severe corrosion is shown in Figure 8-5. The indication was again followed-up with UT and it was found that the minimum remaining ligament was 4.6mm (44% wall loss). The area was extended axially over a length of 150mm and its circumferential extent was 1100mm.

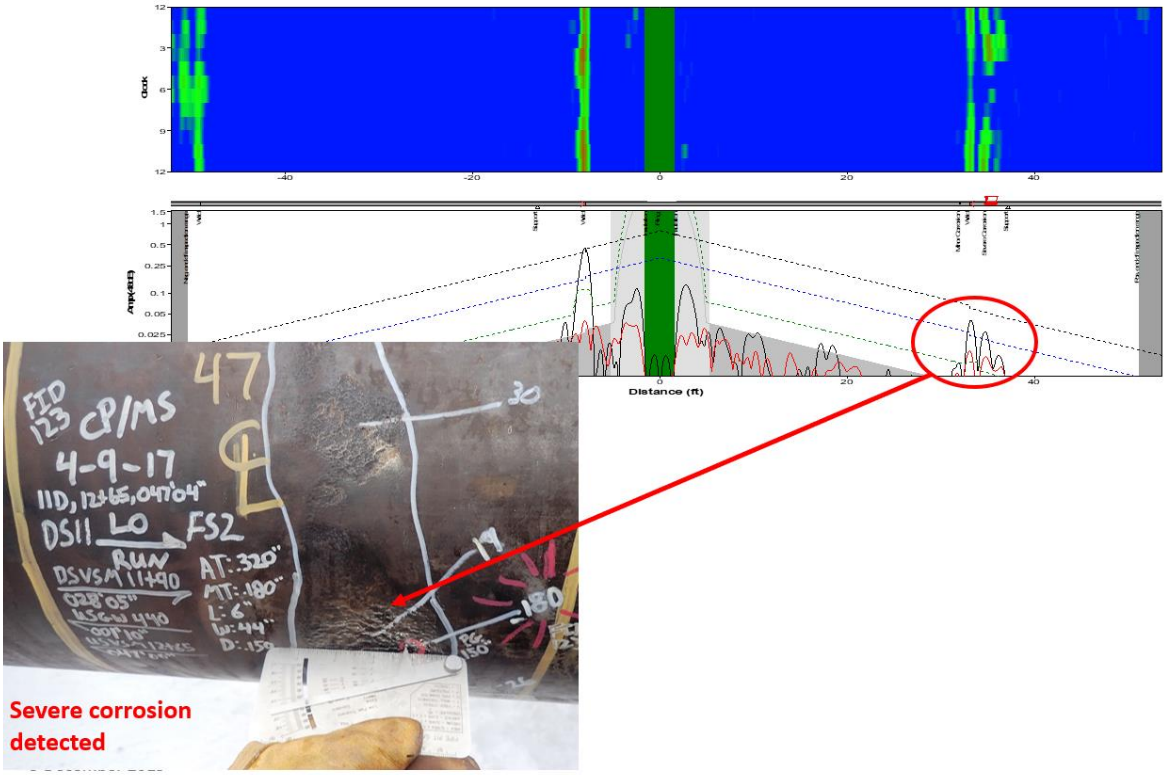

Figure 8-5: GWT data (top) and corresponding area of CUI (bottom), confirmed after removal of the insulation.

8.4.1.3 Case study 3 – CUI/corrosion at a concrete support with steel wear bar

This case study involved a 24” high pressure gas line (14.3mm uncorroded wall thickness) with a painted surface and mineral wool insulation with an alloy cover. The pipe was resting on simple concrete supports with a steel wear bar.

The equipment used comprised a WaveMaker® G4 with a 24” EFC inflatable sensor ring. The test location is shown in Figure 8-6.

Figure 8-6: Test location for inspection of 24" high pressure gas line.

At the inspection location, the test range achieved was about 30m. There were 5 supports within this range and one of them gave an indication of severe loss. The screening gave an estimate of about 40% wall-loss.

The client then removed the insulation at this location and lifted the pipe off the support. The actual wall loss was found to be 38%, which was very close to the GWT estimate of 40%.

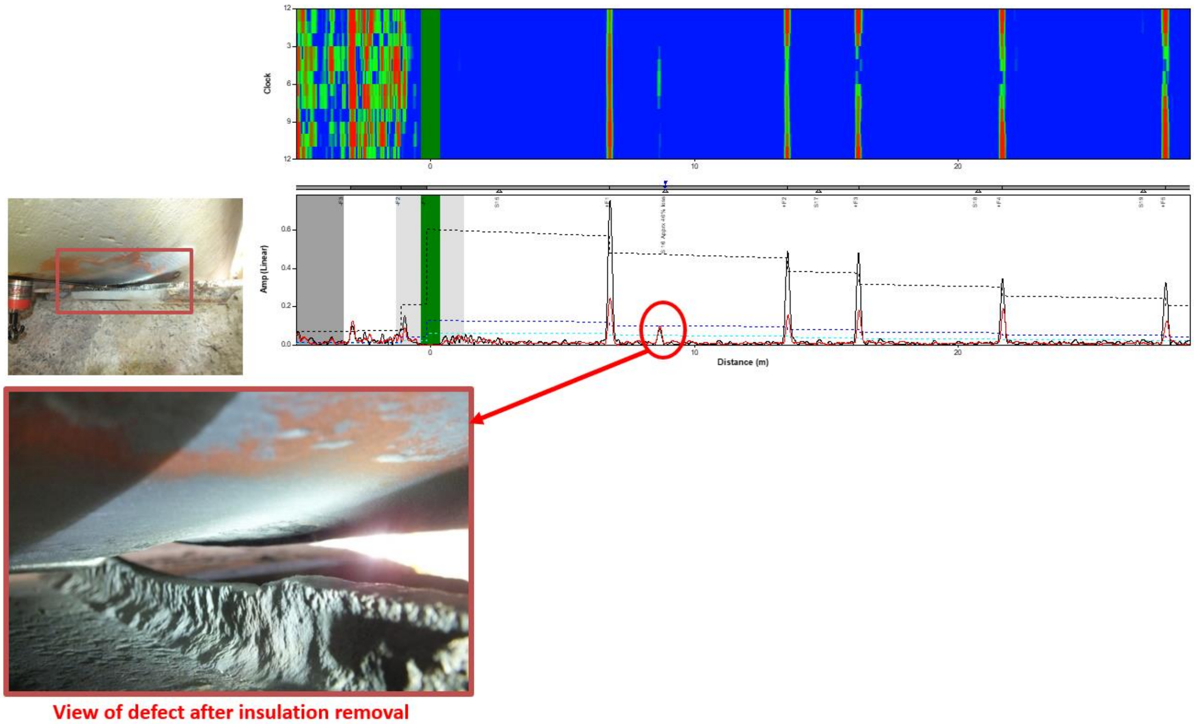

Figure 8-7: GWT data (top) and corresponding area of corrosion at a pipe support (bottom), confirmed after removal of the insulation and lifting of the pipe off the support.

8.4.1.4 Case study 4 – CUI/corrosion on jetty lines

The Teletest® Focus+ system is a Guided Wave NDT Technique developed for screening pipe-work for areas of metal loss damage. It is a pulse-echo system capable of inspecting large volumes of material from a single test point. The initial application was for the detection of corrosion under insulation for petrochemical plant industry, but it has evolved to be used in other inspection situations where pipes or tubes are not accessible. Examples of this are lines that are buried, encased in a sleeve or elevated above the ground.

For this case study, a client in Argentina requested deployment of the Teletest® Focus+ system on two insulated cryogenic jetty lines with 8" and 3" diameters. Each jetty line was approximately 2km in length including several expansion loops and pipe bridges.

The inspection was successful with 100% of both lines being inspected over a 2 week period. Several anomalies were identified during the inspection and follow up was conducted whilst the operators were still on-site. The first anomaly identified was located during the opening shot of the inspection, as shown in Figure 8-8. This anomaly was classified as medium priority and was located at approximately -3m from the tool position.

The A-map scan was also used in the identification of this anomaly (Figure 8-8). The signal from the weld, identified at approximately -13m from the tool position, did not show the expected axi-symmetric response and appeared to have been affected by the anomaly at -3m, which was more centred on the 6 o'clock location. This gave the operator increased confidence that the signal seen at -3m was due to a wall loss defect.

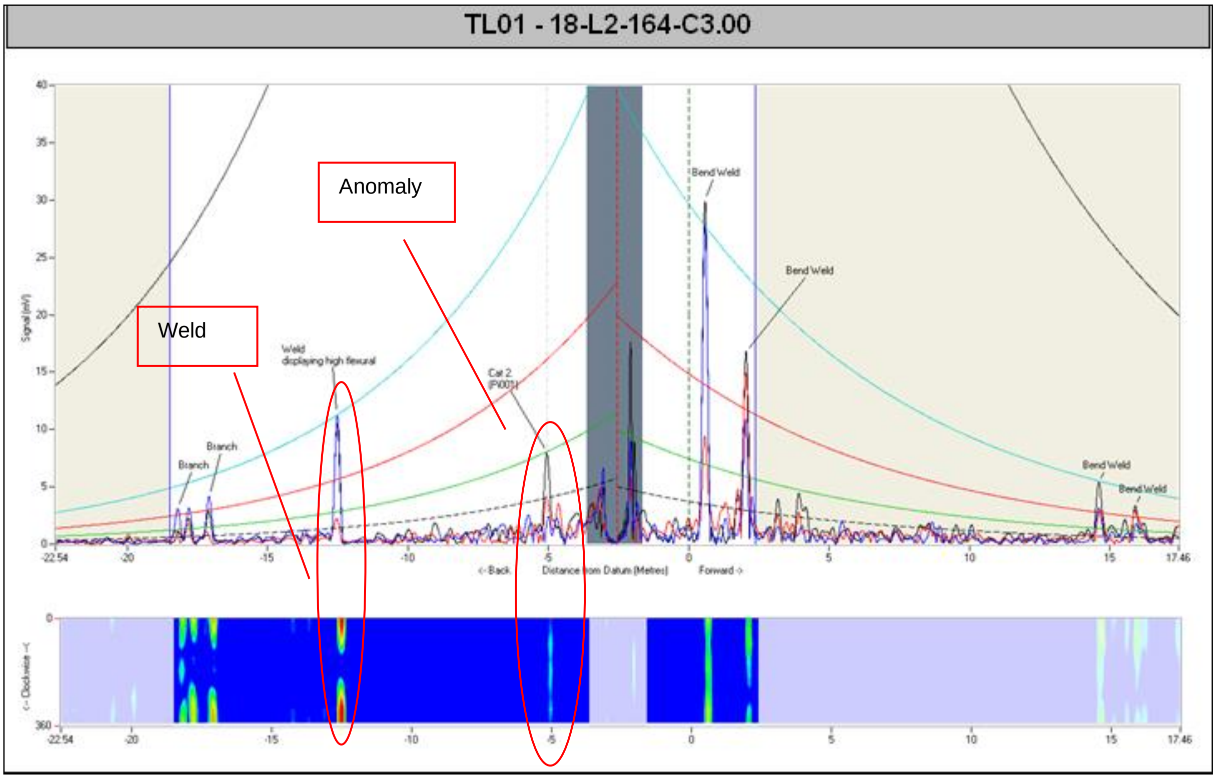

Figure 8-8: TL01~location of detected anomaly.

The location of this indication corresponded to a difficult to access area, as seen in Figure 8-9. The area of interest was directly above water so an access platform had to be erected to allow follow up to take place at this location. Upon removal of the insulation, the inspection team identified external corrosion at the 180° (6 o'clock) position, as seen in Figure 8-10. This area of corrosion was approximately 1 meter in length and 35% wall loss.

Figure 8-9: Location of anomaly area highlighted in Figure 8-8.

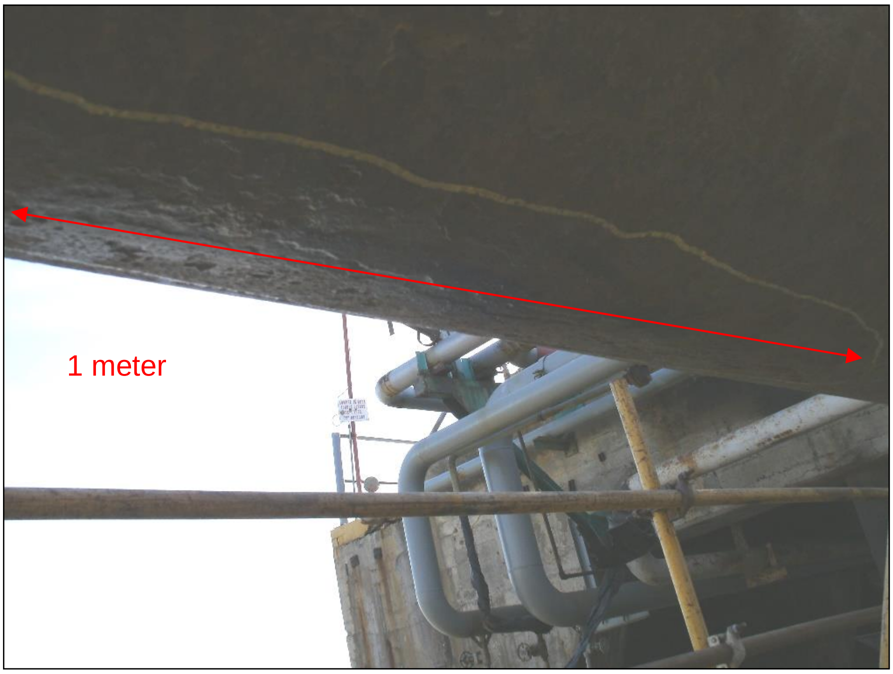

Figure 8-10: Corrosion detected at 6 o'clock (180°).

8.4.1.5 Summary

These case studies have shown that GWT, using the GUL Wavemaker equipment can be applied successfully to locate corrosion under insulation on long, straight lengths of above ground pipelines with diameters ranging from 4" to 24". CUI was found at some support locations (both welded and contact) and on the pipes themselves between the support locations.

The GWT indications were confirmed by removal of the insulation, and the wall losses were measured to be up to about 45% of the nominal wall thickness. The circumferential extents of the areas identified ranged from ~150mm to >1000mm.

Jetty lines (3” and 8”), above water in some locations, were also successfully inspected using the Teletest® Focus+ system. An indication was correctly identified as being due to 6 o’clock CUI in a difficult to access area for follow-up. This had a maximum of 35% wall loss, 1 meter in length.

8.4.2 Pulsed Eddy Current (PEC) survey

This case study was kindly provided by Bilfinger Oil and Gas.

During 2018 an inspection using pulsed eddy current (PEC) was requested by a North Sea offshore operator to identify and locate any areas of corrosion under insulation (CUI) or corrosion under fireproofing (CUF) on a live gas export riser (see Figure 8-11).

Figure 8-11: Live gas export riser in an offshore location.

The pipe had a 16” OD (406mm) with a nominal wall thickness of 16.6mm (sch 60). The insulation thickness was 55mm. The pipe was in an inaccessible location and at height, and rope access was needed to perform the NDT.

The Eddyfi Lyft equipment was used for the PEC inspection. Using the medium sized PEC probe, the footprint size was calculated to be 98mm. The inspection was performed using grid scanning with a circumferential increment of 90mm and an axial increment of 40mm.

In a 2-week inspection campaign, the total axial length of pipe scanned was ~40m, with full circumferential coverage.

Due to the rope access and manual grid scanning mode, in a 6-hour period a total of 4 scans were made each with an axial length of 1000mm, covering the full pipe circumference. The complete dataset was then combined to provide two separate maps of wall thickness, each of which covered a total 4m axial length as shown in Figure 8-12. One of the maps showed the view of half the pipe circumference from the east and the other showed the opposite half, as viewed from the west.

The PEC wall thickness maps showed a general tendency for the lower values on the northern side of the pipe, with some more isolated areas showing the lowest values. The smallest value measured was 76.5% which corresponded to a minimum remaining wall thickness of 12.7mm assuming the calibrated WT of 100% was equal to the nominal value of 16.6mm.

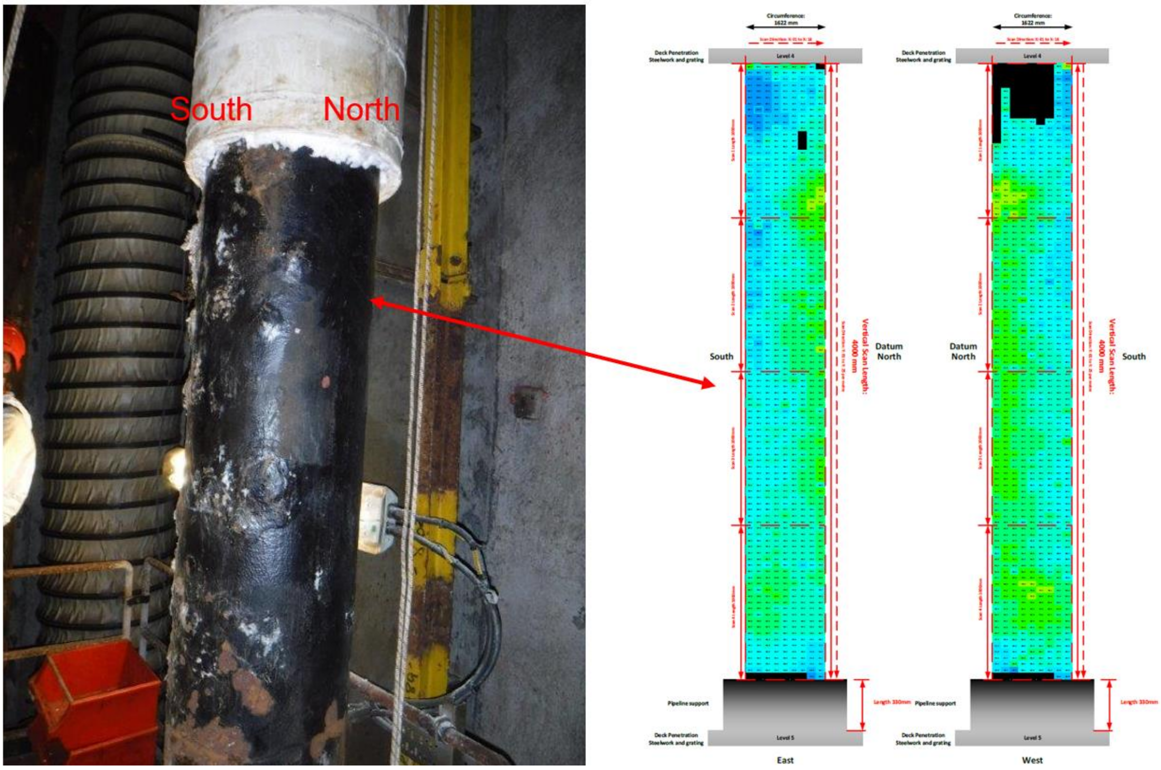

Figure 8-12: Riser with some insulation removed (left) and corresponding PEC scan data (right).

Following the PEC inspection, and in view of the evidence obtained for the presence of CUI/CUF, the operator took the decision to remove the insulation and passive fire protection from the scanned area to allow follow-up inspection using other methods.

Figure 8-13 shows the riser after the insulation removal. Numerous corrosion blisters (scabs) were found, with scab heights of up to ~15-20mm in places.

Figure 8-13: Riser after insulation and passive fire protection removal. Numerous corrosion blisters (scabs) were found (left) with scab heights measured up to ~ 15-20mm in places.

A further decision was then taken to remove the corrosion product to allow a measurement of the remaining wall thickness using 0° pulse-echo UT. The riser after removal of the scabs/blisters is shown in Figure 8-14.

Also shown in Figure 8-14 is a scan of the area showing the lowest remaining wall thickness obtained using a 0° phased array UT method. This showed a minimum remaining wall thickness of 11.5mm. Removing a coating thickness correction of 0.8mm gave a minimum steel thickness of 10.7mm (i.e. a wall loss of 36% compared with the nominal value of 16.6mm).

This remaining wall thickness is somewhat less than the PEC reading of 12.7mm, but this could have been due to the well-known sensor footprint averaging effect that occurs with PEC for localised areas of wall loss (see Appendix A2.7). Alternatively, it may have been due to the wall thickness of the 100% calibration point being less than the nominal value of 16.6mm.

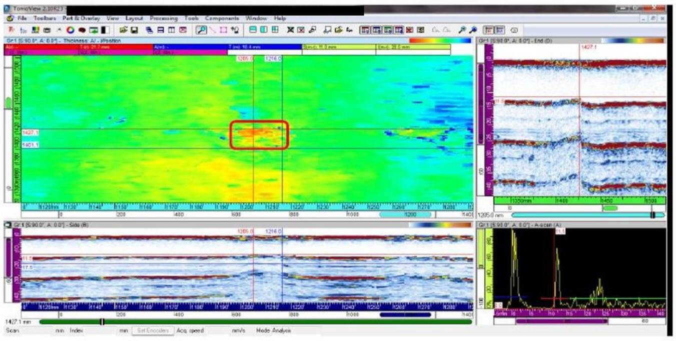

Figure 8-14: Riser after removal of the corrosion product (right) and (left) the 0° PA scan corresponding to the minimum remaining wall thickness position.

This case study has shown that PEC (Eddyfi Lyft) can be used successfully offshore on a high criticality component in an inaccessible location to provide remaining wall thickness measurements over a 4m length of the pipe that indicated the presence of CUI and CUF.

The presence of the corrosion was verified following removal of the insulation/fire proofing and the remaining wall thickness was then measured using a 0° PA method was found to be 64% of the nominal value, following removal of the corrosion product to provide direct access to the external corroded pipe surface.

9 Conclusions

There is continued interest in effective NDT methods for CUI inspection that would avoid the need to remove the insulation to establish the condition of the component, as this is a costly, time consuming operation that usually requires a shutdown. Furthermore, removing the insulation may show that the component is in good condition and free from CUI. However, cost effective and reliable detection of CUI is a significant NDT challenge. Several different NDT methods have been examined since at least the 1990's with varying results in the field. As a result, a common perception is that industry awaits more effective NDT approaches. Consequently, many asset owners rely on rolling programmes that involve stripping of the insulation followed by visual inspection, fabric maintenance if needed and then reinstatement of a new insulation system.

This document provides guidance on a wide range of current NDT methods available for CUI inspection, by detailing for each one their strengths, limitations and areas of applicability. This work should provide operators and NDT service providers with current relevant information on the best methods for this challenging application and lead to a more consistent approach across the industry.

Many factors need to be considered when assessing the applicability of an NDT method for CUI inspection including pipe (or vessel) OD, wall thickness, CUI morphology, the insulation material and thickness, as well as the outer cladding (or weather jacket) material and thickness.

It is important that any users of NDT for CUI are fully aware of the capabilities of the different methods available as these may make them suitable for application to a certain set of components under specified conditions, but not for general usage across a site. Clearly it is unrealistic to expect reliable results to be obtained if the methods are applied outside their range of applicability.

Although moisture detection (or indirect) methods for CUI inspection are covered in this document, they frequently appear to have limited effectiveness for reliable detection of CUI. This is primarily because wet insulation does not necessarily indicate the presence of CUI. CUI will not be present under wet insulation if the coating is in good condition, and CUI can be present under insulation that was dry at the time of inspection (having been previously wet). There can however be some value in application of an indirect method such as infra-red thermography as this can provide clear visualisation of wet areas of insulation which then promotes prompt removal of the insulation to assess the underlying condition of the substrate.

The NDT methods that are currently most widely applied for CUI inspection include guided wave testing (GWT), in both inspection and the more sensitive monitoring modes (e.g. gPIMS) and various radiographic methods. GWT is used extensively in a few geographical areas, mainly on long straight runs of above ground pipework and pipelines with limited attachments, bends and other geometry changes. When used as an inspection method, GWT does however have limitations for the detection of CUI that is circumferentially localised. When used as a monitoring tool, this limitation is less significant.

Conventional radiography using isotope sources and film, or increasingly digital detectors is used for sampling inspection of areas that are most likely to have CUI, particularly in small-bore pipework. Unlike GWT, it can be readily applied to features such as bends, tees and similar geometry changes. The slow throughput of conventional radiography is however a significant limitation.

Alternative radiographic approaches that are used successfully for CUI inspection include scanning systems based on digital detector arrays for inspection of long, straight runs of above ground pipework and pipelines with limited obstructions. In addition, handheld real-time imaging devices (e.g. OpenVision) are also widely used in certain geographic areas (e.g. USA) although their associated radiation hazards make them difficult to operate in compliance with the IRR17 in the UK.

Current technology development with potential for improved CUI inspection is mainly focussed on electromagnetic methods that may overcome some of the limitations of the traditional pulsed-eddy current methods that were originally developed for CUI. The recent development of pulsed-eddy current systems with sensor arrays provides significantly enhanced coverage rates for straight pipes. Also the ability to continuously scan PEC sensors is a notable recent improvement giving faster scanning and increased data sampling. Alternative approaches such as the Russell NDE Bracelet probe, and the prototype Exxam Systems MFECT equipment, gave encouraging results under certain conditions in the most recent HOIS/OGTC trials. Both systems are based on sensor arrays for increased coverage rates on straight pipes.

10 Acknowledgements

The Oil & Gas Technology Centre (OGTC) is thanked for their generous co-funding of this project.

This guidance document built on the results obtained in the first set HOIS CUI trials and the second set of HOIS/OGTC trials. The participants in these trials are thanked for their considerable investments of time, energy and equipment into this project. Participants in the first trials included Bilfinger, CAN, GUL, Oceaneering, Pixel Thermographics, Russell NDE and Shell. The St Fergus site (then managed by Total) kindly provided facilities for the site trials performed in the first trials.

The participants in the second set of electromagnetic NDT trials comprised Bilfinger/Eddyfi (Lyft), Exxam Systems (MFECT), Maxwell NDT/EtherNDE (PECT), Robinson Research Institute (GMR sensors), Russell NDE (Bracelet Probe), and TUV Rheinland Sonovation (Sonopec). Participants in the trials on the small-bore pipes were Acuren (DDA based RT), Bilfinger/Eddyfi (Lyft) and Oceaneering (OpenVision).

Keith Vine (GUL), Paul Jackson (Eddyfi) and Scott Westwater (Bilfinger) are thanked for their provision of material for inclusion in the Section on Case Studies.

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Appendices

Appendix 1 CUI in the oil and gas industry

CONTENTS

A1.1 Key Points

Discussions with HOIS members have identified various key points regarding CUI in the oil and gas industry which include:

- CUI can affect all insulated carbon steel components, including vessels and pipes.
- CUI can also affect duplex/stainless steel components (cracking and pitting).
- The location of CUI is difficult to predict, and it often occurs in unexpected locations.
- CUI generally occurs more rapidly at higher temperatures, within certain limits.
- Coating breakdown is the main precursor to CUI.
- If the coating system is intact, CUI doesn't occur even if the insulation is wet.
- CUI may be present under dry insulation which was wet at some stage previously.
- Moisture ingress, due to lack of weather sealing in the outer cladding, is generally a necessary pre-cursor to CUI. However, in some conditions (e.g. humid environments) moisture can condense onto pipes without any obvious failure of the outer cladding, and eventually cause CUI.

For further information, see API RP 571, API RP 583 and Winnik (2015).

A1.2 Corrosion mechanisms

The corrosion of carbon steel under wet insulation is non uniform general corrosion and/or highly localized pitting. In austenitic stainless steels, the main forms of corrosion are pitting and stress corrosion cracking caused by chlorides.

Carbon steel corrodes when it is contacted by aerated water. Protective coatings, even when present, can be damaged or broken down with age. Insulation can provide an annular space or crevice for the retention of water with full access to oxygen (air) and other corrosive media. The insulation can provide a material that may wick or absorb water and may contribute contaminants that increase or accelerate the corrosion rate. The corrosion rate of carbon steel is principally controlled by the temperature of the steel surface, availability of oxygen and water, and the presence of corrosive contaminant species in the water.

Critical factors listed in API RP 571 are:

- Affected materials are carbon steels, low alloy steels, 300 series SS and duplex stainless steels.

- CUI affects externally insulated piping and equipment and those that are in intermittent service or operate between -12°C and 175°C for carbon and low alloy steels and between 60°C and 205°C for austenitic stainless steels.

- Corrosion rates increase with increasing metal temperature up to the point where the water evaporates quickly. CUI becomes more severe at metal temperatures between 100° and 120° C where water is less likely to vaporise and insulation stays wet longer.

- Design of insulation system, insulation type, temperature, environment are critical factors.

- Poor design and/or installations that allow water to become trapped will increase CUI.

- Cyclic thermal operation or intermittent service can increase corrosion.

- Equipment that operates below the water dew point tends to condense water on the metal surface thus providing a wet environment and increasing the risk of corrosion.
- Damage is aggravated by contaminants that may be leached out of the insulation, such as chlorides.
- Plants located in areas with high annual rainfall or warmer, marine locations are more prone to CUI than plants located in cooler, drier, mid-continent locations.
- Environments that provide airborne contaminants such as chlorides (marine environments, cooling tower drift) or SO_2 (stack emissions) can accelerate corrosion.

Further information on some of these factors is given below.

A1.2.1 Sources of water

There are two primary water sources involved in CUI of carbon steel:

1. Breaks in the weatherproofing can lead to infiltration of water to the metal surface from external sources such as rainfall, drift from cooling towers, condensate falling from cold service equipment, steam discharge, process liquid spillage, spray from fire sprinklers, deluge systems, washrooms, and from condensation on cold surfaces after vapour-barrier damage.
2. Cycling temperatures that vary from below the dew point to above-ambient temperatures can present significant problems. In this case, the classic wet/dry cycle occurs when the cold metal develops water condensation that is then baked off during the hot/dry cycle. The transition from cold/wet to hot/dry includes an interim period of damp/warm conditions with attendant high corrosion rates.

A1.2.2 Contaminants

Chlorides and sulphates are the principal contaminants found under insulation. These may be leached from the insulation materials or from external waterborne or airborne sources. Chlorides and sulphates are particularly detrimental because their respective metal salts are highly soluble in water, and these aqueous solutions have high electrical conductivity. Furthermore, hydrolysis of the metal salts can create acidic conditions leading to localized corrosion.

A1.2.3 Temperature for carbon steels

It is generally accepted that carbon steel operating in the temperature range of about -4°C to 175°C is at the greatest risk from CUI (see API RP 571). Equipment that operates continuously below -4°C usually remains free of corrosion. Corrosion of equipment above 150°C (300°F), well above the boiling point of water, is reduced because the carbon-steel surface remains essentially dry. Corrosion tends to occur at those points of water entry into the insulation system where the temperature is below 150°C (300°F) and when the equipment is idle.

Recent information on the temperature dependence of CUI is as follows (Wiggen, 2019):

- Very High Risk (API 583, 77 – 110°C)
  –Temp 70 –110 °C

- High Risk (API 583)
  –Temp 40 -70°C
  –Temp 110 -120°C
- Medium Risk (API 583)
  –Temp -4 - 40°C
  –Temp 120 -210°C
- Low Risk (EFC no. 55)
  –Temp -12 - -4°C
- Very Low Risk (API 583)
  –Temp < -12°C

A1.2.4 Insulation

CUI of carbon steel is possible under all types of insulation. The rate of corrosion may vary depending on the characteristics of the insulation material. Some insulation materials contain water-leachable salts that may contribute to corrosion, and some foams may contain residual compounds that react with water to form an acidic environment. The water retention, permeability, and wettability properties of the insulation material also influence the corrosion of carbon steel.

A1.2.5 Corrosion of Stainless Steel Under Insulation

CUI in austenitic stainless steel is manifested by chloride-induced stress corrosion cracking (CISCC), commonly referred to as external stress corrosion cracking (ESCC) because the source of chlorides is external to the process environment. ESCC of austenitic stainless steel is possible when the equipment is contacted by aerated water, chlorides, or contaminants in the temperature range of 60° to 205°C (API RP 571) and the presence of tensile stresses.

The mode of cracking is normally transgranular. It is well established that the propensity for ESCC is greatest when the following conditions are present:

- A susceptible 300 series austenitic stainless steel.
- The presence of residual or applied surface tensile stresses.
- The presence of chlorides, bromide, and fluoride ions may also be involved.
- Metal temperature in the range 50° to 150°C.
- The presence of an electrolyte (water).

For ESCC to develop, sufficient tensile stress must be present in the material. If the tensile stress is eliminated or greatly reduced, cracking will not occur. The threshold stress required to develop cracking depends somewhat on the severity of the cracking medium. Most mill products, such as sheet, plate, pipe, and tubing, contain enough residual tensile stresses from processing to develop cracks without external stresses. When the austenitic stainless steels are cold formed and welded, additional stresses are imposed. The incidence of ESCC is greater in process piping because of the high hoop stresses normally present in piping systems. As the total stress increases, the potential for ESCC increases.

A1.2.6 Summary

CUI results from the collection of water or vapour between a metal surface and thermal insulation. On carbon steels CUI generally occurs in the form of general corrosion or localised corrosion. In austenitic stainless steels, such as the 18-chromium-8-nickel (18-8) or AISI 300 series stainless steels, CUI often occurs as stress corrosion cracking (SCC) and pitting.

CUI typically occurs where water can collect by gravity, such as at penetrations to insulation or where attachments may channel drainage. On horizontal piping, damage often occurs at the 6 o'clock position, while on vertical pipe runs damage frequently occurs at the bottom. However, there have been many examples of CUI occurring in unexpected locations.

In carbon and low alloy steels CUI results in large areas of wet scale. In austenitic stainless steels chloride SCC often occurs at welds and in non-stress relieved bends. Although CUI can occur over a broad temperature range of -12 to > 210°C, the greatest potential and most severe environment is between about 70 and 110°C.

A1.3 Types of insulation

There are many different types of insulation used within the oil and gas industry, beneath which CUI may occur. In addition, the insulation is often surrounded by metallic cladding or jacketing.

There may also be metallic materials within the insulation, in the form of chicken wire and/or perforated sleeves.

A comprehensive description of all the types of insulation and cladding/jacketing materials used in the oil and gas industry is beyond the scope of the present document and may be found elsewhere (e.g. Appendices H & G of Winnik, 2008).

The insulation may be used for a number of purposes including mainly thermal insulation, noise reduction and fire protection.

The most commonly used insulation materials include:

- Rockwool
- Foam Glass
- Elastomeric Foam (increasing use recently)
- Firemaster
- Noise blanket

There may be more than one type of insulation present at once, for example foam glass surrounded by Firemaster, or foam glass + Rockwool + noise blanket.

The total thickness of insulation is very variable but may typically range from 50mm to at least 100mm.

A1.4 External claddings

Traditionally, the main types of the outer metallic cladding have been:

- Aluminised steel
- Aluminium-zinc coated steel
- Galvanised steel
- Stainless steel
- Aluminium

Recently there is increased usage of non-metallic claddings such as Ulvashield, Fibraroll, and Terostat (pre-applied to Foam Glass).

A1.5 Coatings

A1.5.1 Introduction

A detailed description of coating systems and their implications for CUI is beyond the scope of the present document.

However, it is important to note that CUI does not occur if the coating system was applied correctly and is still intact. Even if the insulation is saturated with water, corrosion will not occur unless the coating has broken down. Once this breakdown occurs, wet insulation can result in rapid corrosion.

A1.5.2 Organic coating systems

The application of organic coatings on both carbon and stainless-steel equipment beneath insulation is an effective method of having a physical barrier to corrosive electrolytes and thereby preventing corrosion.

The average life cycle of a coating system is of the order of 5 to 13 years. In some cases, when a correctly selected and applied coating system is used, a 20-year service life can be achieved.

Some of the parameters that need to be considered when selecting a coating system include coating selection, surface-preparation requirements, environmental requirements, compatibility with insulating material, coating tests, coating vendor selection, specifications, inspection, and selection of a coating applicator.

For more information on the selection of protective coatings from the CUI perspective, see Winnik (2008).

A1.5.3 Thermal spray aluminium (TSA)

For conditions too severe for organic coatings, such as temperature cycling above and below 150°C, and more generally in some cases, TSA is used for corrosion protection beneath insulation. Provided it is applied correctly, with appropriate surface preparation etc., TSA protects equipment by acting as a barrier coating and serves as a sacrificial anode, protecting the substrate at the sites of any chips or breaks in the coating.

Usage of TSA as an effective means of avoiding loss of integrity due to CUI is heavily promoted by some, especially ExxonMobil (e.g. Winnik, 2008; 2015). Note that inspection of TSA components may present some issues as highlighted in previous HOIS work, see Burch *et al*. (2013) and Peramatzis *et al.* (2010).

Within the HOIS membership, there have been a number of reports of issues with TSA coated components and rapid development of CUI. In a recent conference paper, Begg (2019) from TWI appeared to acknowledge that in certain conditions TSA coated components can experience rapid degradation. He reported that occluded environments (i.e. crevices containing liquid under damaged coatings) can lead to autocatalytic-type behaviour where pH changes result in rapid consumption of coating, which could be very relevant for certain CUI conditions. Corrosion of the coating was said to be possible for both low and high pH conditions (<4 and >8.5).

A1.5.4 Personnel protection cages

In many instances, thermal insulation is used for personnel protection from hot surfaces. The unnecessary use of thermal insulation creates a location for potential corrosion. In these cases, wire “standoff” cages can be used. These cages are simple in design, low in cost, and eliminate the concerns with CUI. However, the attachment points of these cages to hot surfaces can give rise to corrosion i.e. between the substrate and attachment brackets if an inappropriate insulation material is used. Nevertheless, the overall risk of CUI related issues is reduced because any severe corrosion can then be seen visually.

An example of a personnel protection cage is given in Figure A1-1.

Figure A1-1: An example of a personnel protection cage (courtesy Total).

A1.6 Examples of CUI

Some examples of CUI following removal of the insulation are shown below.

Figure A1-2: Some examples of CUI

Figure A1-3: Failure of a 4" pipe caused by CUI

Figure A1-4: A further example of CUI, following insulation removal (courtesy Total)

Appendix 2 NDT methods for CUI

CONTENTS

A2.1 Introduction

This Appendix contains descriptions of fully and almost fully developed (i.e. TRL level of at least 8) NDT methods for CUI inspection, with the emphasis on those capable of being applied to components with the insulation (or fireproofing) still in place. To be included in this section, the methods need to have been used in-service for routine inspections, which have included inspection of CUI.

Developmental methods, considered to have lower TRLs (i.e. ≤ 7), that have not yet been used for routine in-service site inspections are covered separately, in Appendix 3.

The methods in the present Appendix vary from those with the potential to screen large areas quickly for CUI to those for which more time is needed for a local inspection with the aim of quantifying the severity of the CUI in terms of the area affected and the minimum remaining wall thickness.

A number of moisture detection (indirect) NDT methods are also available. These methods are generally aimed at the detection of moisture under cladding within the insulation or on the pipe surface. The presence of moisture alone does not however indicate the presence of CUI – coating breakdown is also needed for the formation of CUI. In addition, areas of previously wet insulation with CUI, may have dried out at the time of the inspection. Nevertheless, the reliable detection of the presence of moisture, especially if done regularly, may form part of an integrity management strategy for CUI.

The methods covered in this Appendix are taken from a number of sources, including the earlier HOIS reports (Wall and Krol, 1999; Burch, 2005), API 583, Winnik (2008), HSE RR 659 (Hardie, 2009), and also the replies to the members' questionnaires issued in phase one of the present project (see Burch, 2013). Information obtained from both sets of HOIS CUI trials is also included where applicable (Burch and Kitchener, 2016; Burch and Collett 2019).

The aim of this Appendix is to describe the basis of the various NDT methods, and how they can be applied for CUI inspection. Summaries which include the main strengths and limitations of each method are given.

A2.2 Visual inspection prior to insulation removal

General visual inspection without removal of insulation is extensively used to assess the condition of the pipework and to check for possible indicators of CUI. This is however an indirect method as any CUI is invisible underneath the insulation.

The effectiveness of this form of inspection may be quite variable, and there could be potential for improvements (better technician training, improved reporting of information and overall management of the process).

The following is a list of susceptible areas and conditions that a visual inspection survey should aim to check for:

- Weathered, split or missing mastic moisture barriers on piping, vessel heads and sidewalls, above supports and around nozzles.
- 'Dead' (inelastic), loose or missing caulking at seams and connections.
- Punctured, split or corroded metal jacketing.
- Improper installation interfering with water runoff.
- Mould, mildew or moisture at insulation support rings or vacuum rings on vessels.
- Red stains or white deposits on jacketing.
- Unprotected components where a section of insulation or a panel of cladding has been removed.
- Unsealed metal wall thickness test points.
- Flashing that does not shed water.
- Gaps around pipe hangers and other protrusions.
- Gaps in jackets at top of vertical pipe runs.
- Open joints in jackets from physical damage.
- Attachments, nozzles, ladders, supports, gangways, etc.
- Cladding that is sagging under the weight of the wet insulation inside.

In many cases the above conditions may require further investigation and inspection due to the increased risk of CUI, as well as fabric maintenance to repair the condition of the insulation.

Summary

Method	Visual inspection without insulation removal
Basis	Looking for indirect visual evidence of CUI e.g. rust stains, wet insulation, damaged insulation and weather barriers, etc.
Strengths	Good for assessing external condition of insulation. Comparatively fast, global, widely used. Applicable to nearly all components.
Limitations	Indirect, CUI not directly visible and may be present without any tell-tales such as rust staining. Also, it is impossible to judge the severity of any CUI present.

A2.3 Direct inspection by temporary partial insulation removal

As an alternative to full removal of insulation followed by visual inspection, it is possible to perform limited/temporary removal of insulation and/or make holes in the insulation. One approach is to remove the cladding and then temporarily partially remove the insulation, hence allowing direct visual inspection of the pipe surface. If no corrosion is evident, the insulation can be readily repositioned and the cladding re-applied.

Alternatively, following cladding removal, holes can be cut in the insulation to expose the equipment external surface for inspection thus creating inspection windows. Windows should be cut where CUI is most likely such as at poorly sealed insulation penetrations, at low points in the piping system where water can collect, at insulation support rings or vessel stiffening rings, or at areas where the insulation jacketing is in poor condition and water can penetrate the insulation system.

The areas where insulation is removed should be large enough to be representative of the condition of the equipment. It may be necessary to examine several locations or cut several windows in susceptible locations due to the difficulty in predicting where CUI damage has occurred.

For example, on a large drum or tower it may be necessary to remove a vertical strip of insulation to represent different temperature zones in the equipment, and to locate stiffener or insulation support rings. Once located, selected insulation support rings or stiffeners may then be de-insulated around the circumference of the vessel to locate areas where degradation may be the most severe.

A variant of partial insulation removal is to perform visual examination or UT inspection at inspection ports in the insulation. Other measurements such as moisture detection can also be made.

This approach can be of limited value due to the small amount of surface area exposed for inspection and the risk of the holes making subsequent water ingress possible.

Summary

Method	**Inspection through access ports through insulation**
Basis	Limited and/or temporary removal of sections of insulation in areas most likely to have CUI, followed by visual inspection
Strengths	• Costs associated with insulation removal/reinstallation are significantly reduced compared to complete removal of insulation • Limited exposure to hot surfaces for personnel
Limitations	• CUI damage can be missed since only a limited area of the equipment is inspected • Special precautions are necessary on asbestos insulated systems • Windows cut in insulation pose a potential leak path for water ingress if insulation not effectively repaired/sealed

A2.4 Moisture detection (indirect) methods

A2.4.1 Introduction

There are a number of methods that can be used for detection of moisture in insulation. As such they are referred to as indirect methods for CUI detection, as the presence of moisture in insulation may or may not be associated with CUI.

With methods intended to detect moisture in insulation, it is important to note the following:

- If the coating system is intact, CUI will not form under wet insulation although eventually there will be coating breakdown followed by CUI.
- Dry insulation does not exclude the possibility of CUI being present. Previously wet insulation could have dried out at the time of inspection.
- Regular monitoring of insulation for the presence of moisture may be valuable as insulation that has never been wet is unlikely to have CUI. However if the CUI mechanism involves wet/dry cycling below/above the dew point (see Appendix A1.2.1), the condensation that forms on the pipe may never result in detectably moist insulation.
- Visual examination may be sufficient to indicate a strong likelihood of the insulation being wet (e.g. through presence of rust staining and other tell-tales, visibly damaged weatherproofing).

Methods for detecting moisture in insulation include simple water collection devices, which must be installed into the insulation and two non-contacting methods - infrared thermography and neutron backscatter.

With either of these two non-contacting methods, the possibility of intermittent wetting and drying-out of insulation, especially on hot plant and pipework, leading to a misleading result, needs to be kept in mind.

In principle, if a component, operating at a temperature consistently above the dew point, is regularly monitored by these indirect methods and is always found to be dry, then the possibility of CUI occurring is likely to be low, provided that any moisture present can be found reliably.

A2.4.2 Water collectors

Principle of method and application for CUI detection

Water collectors are devices that aim to detect the presence of water in insulation by collecting it as it drains out from an exit point positioned at a low point in the insulated system (e.g. the 6 o'clock position for a horizontal pipe). However, water transport within an insulated system is poorly understood which may complicate the positioning of these devices.

One such device is called H2Obvious, as shown in Figure A2-1 and Figure A2-2. Other devices are also available (e.g. the Benarx WUI Drain Plug http://www.benarx.com/products/fire-series/drain-plug/ - see Figure A2-3).

Installation of the H2Obvious device involves drilling a 30mm diameter hole through any metal cladding and then boring out a similar diameter plug of insulation material.

With H2Obvious, fluid enters the collection funnel and then drains into a float chamber/vial within the device and, if conductive, starts an alarm with the flashing LED.

The fluid present can then be provisionally identified from the following alternative conditions:

a) Float rises but no flashing light -probably hydrocarbon
b) Float rises with flashing light -probably substantially water

The H2Obvious vial can then be unscrewed from the collector funnel, capped and sent to a laboratory for further analysis. From this sample, hydrocarbon or other process product (if any) can be identified. It is unclear how hydrocarbons could enter the vial unless a loss of integrity had occurred.

If the collected fluid is identified as clear water; it can be assumed that little or no corrosion/deterioration has taken place and that the protective coating on the pipe is sound. Water containing large amounts of iron oxide is indicative of active CUI.

Figure A2-1: H2Obvious device installed on a UK refinery

Figure A2-2: H2Obvious devices installed on a UK refinery

Figure A2-3: The Benarx WUI Plug is a tool for draining and detecting the presence of water under the insulation

Summary

Method	**Water collectors such as H2Obvious and other devices (e.g. the Benarx WUI Drain Plug)**
Basis:	Collection of fluids draining out of the insulated component by means of devices installed through the outer cladding and insulation.
Strengths:	• Positive detection of liquid water in insulation • Analysis of collected water can indicate active CUI • Low cost • Continuous monitoring
Limitations:	• Detects only liquid water in insulation, but not extent of any CUI that may be present • Effectiveness for CUI caused by condensation onto pipes below the dew point unclear, as the surrounding insulation may not then be wet. • Limited to spot sampling in areas most expected to develop CUI • Limited information available on effectiveness in practice.
Overall:	May be useful as part of a dedicated CUI monitoring programme.

A2.4.3 Passive infra-red thermography

Overview of method

Passive infrared thermography is an indirect method for CUI inspection, in that it seeks to locate areas of wet insulation which may (or may not) be associated with CUI. Thermography is a rapid, non-contacting screening method in which the infrared camera can be up to about 20m from the component.

The method requires there to be a temperature differential between the pipe contents and the ambient conditions outside the pipe. Wet insulation generally has a higher thermal conductivity than dry insulation. Thus, if the product is hotter than the ambient temperature, wet insulation should therefore cause the surface temperature to be higher than that of dry areas of insulation.

Hence in principle, the method is quite straightforward. An infrared camera is used to monitor the apparent surface temperature of components; wet insulation can be detected under the right conditions, as it has a different surface temperature to surrounding dry areas. The larger the temperature differential, the more reliably the method should be able to identify moisture in the insulation.

There have been recent improvements in infrared camera technology, which have increased the quality of the resultant images. Figure A2-4 shows a high-end infrared camera for industrial applications. The weight and cost of infrared cameras have also been significantly reduced. Temperature differences as small as 0.05°C can be detected with modern, hand-held cameras. Results can be readily recorded as colour coded (false-colour) images in digital form, see Figure A2-5 for an example.

Figure A2-4: A high-end infrared camera for industrial applications

Recently, remotely operated drones/UAVs have been used to deploy thermal cameras for moisture detection surveys from the air, which is an advantage of this method as it increases inspection speed and reduces any inaccessibility issues.

Methods for improving reliability of the method

Experiences of the effectiveness of infra-red thermography for detection of moist insulation are mixed. For optimum results, it may be important to fully understand the capabilities and limitations of the method, and to perform the inspection under appropriate weather and other conditions, as outlined below.

For thermography to show moist areas of insulation, there must be a temperature differential across the thickness of the component (from inside the pipe/vessel to the outside) of at least 10°C (API 583). However, based on reported feedback received from some vendors, this temperature differential might not be sufficient and in their experience 25- 30°C is a more realistic value. This accords with Hardie (2009) that states that for “CUI inspections a 30°C temperature gradient across the insulation (between pipe & environment) is desired to ensure detection."

Issues due to the low infra-red emissivity of the cladding material can limit the effectiveness of this method. Newly installed metallic cladding materials (e.g. stainless steel or Aluzinc in good condition) generally have low emissivity, so that the apparent surface temperature obtained using an infra-red camera is significantly different from its actual value. Surfaces with low emissivity also have high reflectivity so interpretation may be hampered by reflections from other plant components at different temperatures.

Weathered metallic coatings are beneficial for the effectiveness of this method, as they have higher emissivities and lower reflectivities than those in good condition.

There are some suggestions (e.g. API 583) that conducting the infrared survey 2-3 hours after the sun has set can be advantageous since wet insulation will maintain the heat absorbed from solar rays better than dry insulation. This can tend to promote more contrast in the thermograph but seems unlikely to be effective in all cases. Some also advise that thermographic inspection for CUI should be done in the absence of strong gusty winds since wet insulation maintains its heat longer in the non-windy conditions. The effects of any external metal cladding on these recommendations are however unclear.

Overall, there may be some scope for a more detailed investigation into, and review of, the factors that can contribute to improved reliability of infrared thermography for detection of wet insulation in oil and gas environments. There are understood to be examples of this method providing useful information for CUI management, but others believe the method has little value.

Examples

The examples shown in Figure A2-5 and Figure A2-6 are taken from the Infrared Vision website. In these cases, areas of damp/moist insulation are shown very clearly as hotter areas in the infrared images – presumably the product was at a higher temperature than ambient in these cases. In Figure A2-5, the damp areas of insulation appear to correspond to penetrations in the cladding for the vessel top steelwork walkway.

Figure A2-5: De-Salter vessel showing water intrusion under the insulation, apparently at penetrations for the walkway along the top of the vessel (courtesy Infrared Vision).

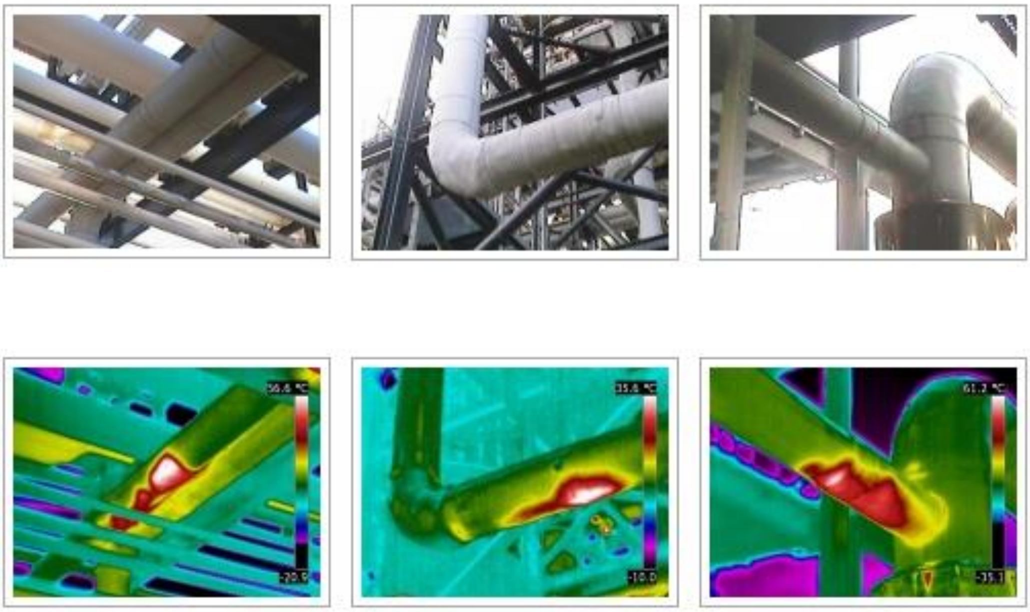


Figure A2-6: Hot spots on areas of process pipework showing increased thermal conductivity due to moist insulation (courtesy Infrared Vision).

HOIS trial results

A HOIS IR thermography site trial (Burch and Kitchener, 2016) was performed by a company experienced in the application of thermography for detection of moist/wet insulation which can indicate the presence of CUI. The survey was conducted on trains 2 and 3 at an onshore oil and gas site, which contained pipes between 6" and 12" sch 20 in diameter, with an operating temperature range of c.180°C to 230°C. The insulation comprised 40 - 60mm of Rockwool, with galvanised steel cladding. In the most part, the cladding was weathered and dirty which made a thermographic survey viable, in the view of the inspector.

The survey using a handheld IR camera from ground level identified numerous areas where it was suspected that corrosion under insulation might have been taking place due to elevated surface temperatures indicative of wet insulation. Images were recorded for all suspect areas, but not the remainder of the piping.

A full strip of the insulation material was carried out after the survey, for full categorisation of the actual condition of the piping and comparison with the thermography results.

The comparison between the thermography results and the full strip showed that corrosion was found under the insulation areas highlighted in the IR survey, as illustrated in the examples given in Figure A2-7 and Figure A2-8.

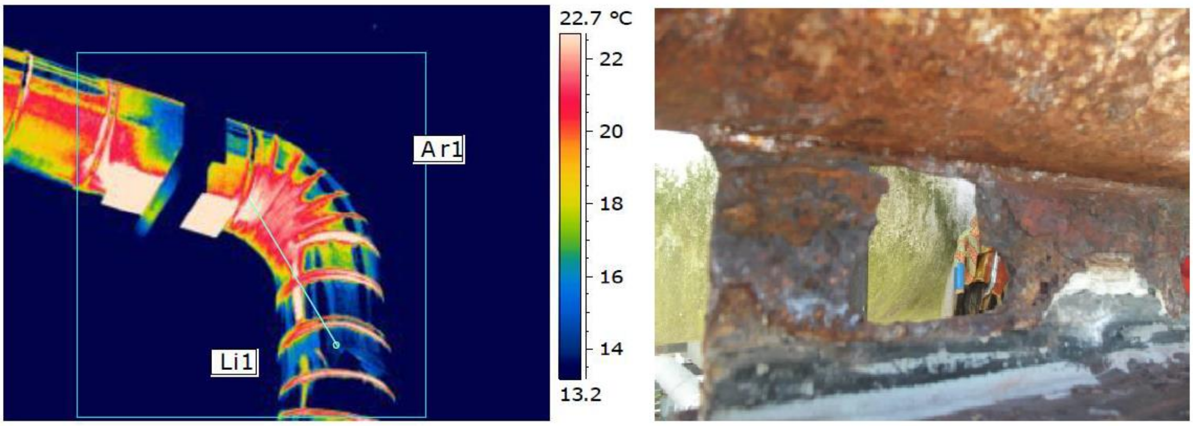


Figure A2-7: An example of an area of corrosion found during the thermography site trial. The infrared image is shown on the left, and photographs of the corresponding insulation-stripped area is on the right. The 8" pipe was found to have a remaining WT of < 4mm.

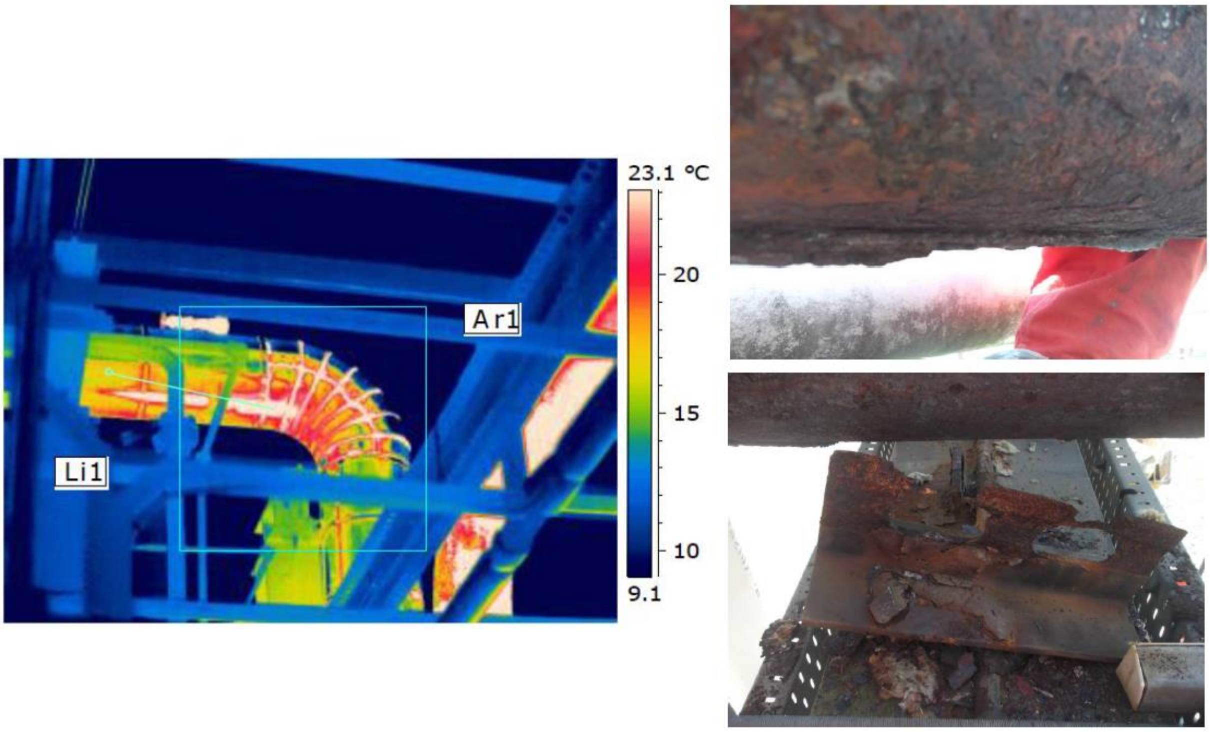


Figure A2-8: An example of an area of corrosion found during the site thermography trial. The infrared image is shown on the left, and photographs of the corresponding insulation-stripped area is on the right. The 8" pipe was found to have a remaining WT of < 3.7mm.

Overall the asset owner stated that these areas of apparent water ingress would have been identified for stripping anyway as significant degradation to the cladding was visible.

More significantly, the IR survey was found to have missed the worst CUI affected area, which was identified after the insulation had been stripped away. Unlike other areas, there was no evidence of any degradation of the cladding to suggest that it was an area of concern. As this area had not been identified during the IR survey, there were no stored IR images collected for later examination. Hence no investigation was possible into the reasons for the failure to report this area in the IR survey.

It is unclear if these areas of degradation would have been visible from the IR survey position on the ground. Low emissivity due to a clean metallic insulation surface may also have been a factor (many sections of the lines inspected had a build-up of dirt & grime which increased emissivity and hence improved the sensitivity of the thermography to wet insulation). Another possibility is that the insulation could have previously been damp but had subsequently dried out.

Nevertheless, for whatever reasons, the IR survey did not locate the sections of the pipe trains containing the most severe examples of CUI, although it did correctly indicate many other areas of corrosion.

Hence, the asset owner considered that the thermography survey did not increase the chance of detection of CUI, as the corroded areas it identified were visible from the cladding degradation. The method also missed the most corroded area in the survey, which indicates that it cannot be relied upon to identify areas of concern. However, there was considered to be some value in the visualisation of wet insulation, to support a case for urgent stripping of the insulation from the piping.

Summary

Method	**Passive infra-red thermography**
Basis:	Portable IR camera used to measure surface temperature of pipes/vessels looking for changes caused by wet insulation which has higher thermal conductivity than dry insulation.
Strengths:	• Fast, global screening method. • Can be applied remotely (e.g. using a drone/UAV or from ground level) without contacting the surface – hence avoiding need for scaffolding etc. • Applicable to wide range of components, including pipes and vessels. • Regular monitoring could identify components that do not get wet and are hence unlikely to develop CUI.
Limitations:	• Only sensitive to wet insulation, not CUI. • Needs a temperature difference between the pipe and ambient (estimates of required temperature differential but the more realistic values are ~30°C) • Metal cladding, if in good condition, can cause problems (low emissivity and reflections). • Areas of wet insulation may be visible visually through tell-tales without a need for IR thermography • Potentially limited coverage as some components may be in obscured locations (e.g. in pipe racks) and not visible from a ground-based survey.
Overall:	Unreliable if used as a one-off on its own. May be more effective as part of a dedicated monitoring program. If the cladding is metallic, a weathered condition appears to be necessary to make the method viable.

A2.4.4 Neutron Backscatter (Hydrotector)

Overview of method

Neutron Backscatter is another indirect method for CUI inspection, in that it attempts to locate areas of wet insulation which may (or may not) be associated with CUI.

The neutron backscatter method is based on the moderating effect that hydrogen atoms, present in compounds such as water and oil, have on the energy level of neutrons. A beam of high energy neutrons incident on material containing hydrogen atoms causes the fast neutrons to be moderated into low energy or thermal neutrons, which are scattered in all directions including backwards towards the source/detector assembly.

Portable fast neutron sources for this application are generally based on isotope sources such as an Americium 241 Beryllium compound, which has a half-life of 458 years. This source produces 4.5 MeV neutrons via a reaction in which the Beryllium absorbs an alpha and emits a neutron [the 9Be(a,n)12C reaction]. This source also emits gamma rays as well as the fast neutrons, with associated radiation hazards.

The thermal neutrons are scattered in all directions but have a short travel path. Some of these thermal neutrons are scattered back towards the scanning head and are counted by a detector. The more hydrogen atoms present in a material, the more thermal neutrons are produced and counted by the detector.

It should be noted that this method detects hydrogen atoms. Therefore, these devices cannot distinguish between water, hydrocarbons, acids, bases, and organic liquids. However, the presence of any of these fluids may warrant follow-up inspection, depending on the circumstances – hydrocarbons and water are of course frequently found inside pipes and vessels in the oil and gas industry and steel pipe/vessel walls are relatively transparent to neutrons. Hence it is possible that liquid product in a component may be mistaken for wet insulation using this method.

Figure A2-9 shows a photograph of the Hydrotector instrument and its principle of operation.

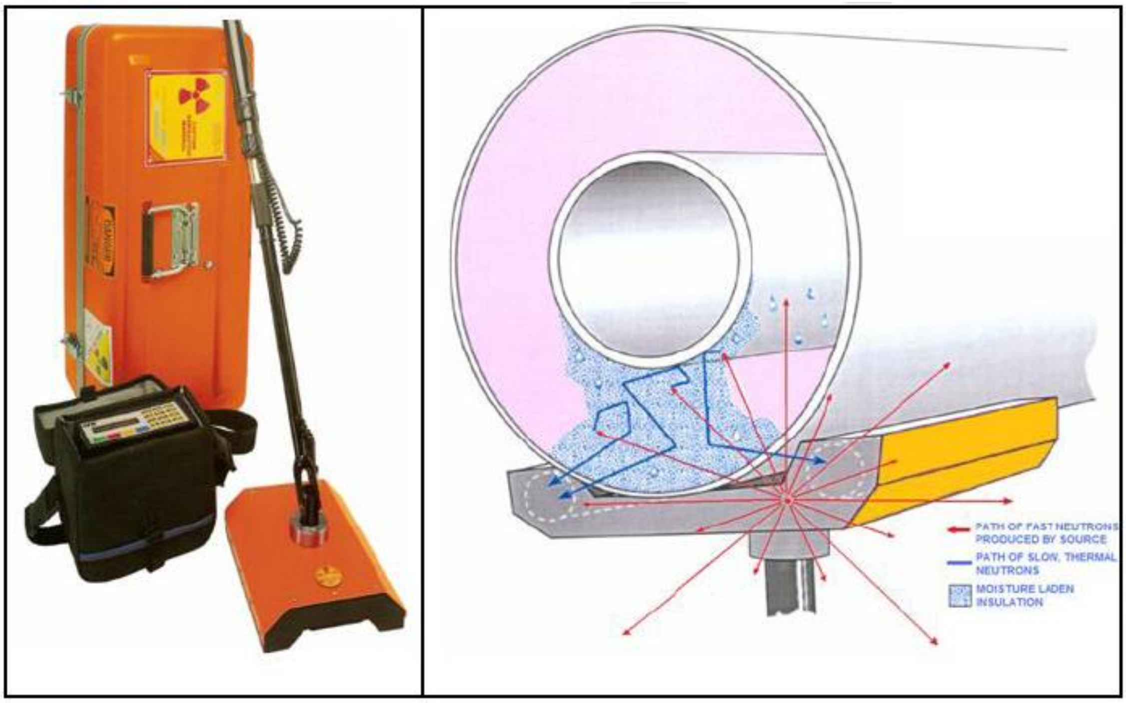


Figure A2-9: Photo of the Hydrotector system (left) and principle of operation (right).

It is important to note that this is a radiological device, and a specific licence is required to possess and store it, as with other gamma-ray emitting isotope sources used for radiography. Operators must be adequately trained in radiation safety and the usage of the equipment.

In the UK, the equipment would need to be demonstrated to be operated in accordance with the IRR17 which details the legal requirements for operating equipment that generates ionising radiation. Other standards apply outside the UK.

Application to CUI inspection

Figure A2-10 shows the Hydrotector system being used for detection of moisture in insulation – the source and detector need to be placed in contact with the insulation but the long telescopic arm allows access to some components without the need for scaffolding or rope access etc. A local increase in the detector counts as the instrument is scanned along/around the component can indicate the presence of the hydrogen atoms present in water, and hence wet insulation.

Figure A2-10: Hydrotector system being used for CUI inspection.

This is said to be a relatively easy to use method which allows rapid scanning of insulated components. However, the method has significant radiological safety hazards and there can be false readings caused by water and hydrocarbon products in the components under inspection, as the neutrons involved can readily penetrate steel.

This method is little used in the UK at least, according to the HOIS members CUI questionnaire responses (Burch 2013).

HOIS trial results

This method was not shortlisted for a HOIS trial due to its low level of current usage in the UK and hence there were no trial results.

Summary

Method:	**Neutron backscatter - Hydrotector**
Basis:	Uses an isotope source of fast neutrons – and a detector which looks for backscattered thermal neutrons from areas of wet insulation containing the hydrogen atoms that have moderated the neutrons.
Strengths:	Relatively fast, applicable to pipes and vessels
Limitations:	• Radiation safety issues, • At best only finds wet insulation, not CUI • Can be affected by liquid product inside the component. • Some components may be inaccessible without scaffolding/rope access etc. • Little current usage in the UK at least.
Overall:	Seldom used method nowadays due to radiation safety issues and low reliability – at best finds only wet insulation not CUI

A2.5 Guided wave testing (GWT)

A2.5.1 Introduction

Guided wave testing (GWT) uses a ring of ultrasonic sensors clamped around the pipe. For CUI inspection, an access window in the insulation needs to be created in order for the ring to be attached directly to the pipe.

Guided waves are then generated and transmitted in both directions along the pipe as illustrated in Figure A2-11. Changes in the pipe wall cross section produce reflected signals which are then directed back to the sensor and form part of the detected return echo waveform.

In ideal cases, guided waves can propagate several tens of metres along a pipe and so a considerable length of pipe can be inspected from a single access position.

Welds and other features to which the pipe is connected (e.g. pipe supports, tees, flanges) also produce return echoes which must be distinguished from those due to corrosion.

Guided waves can propagate round bends, but this generates mode conversions which complicate the data interpretation and reduce sensitivity. Guided waves cannot propagate through flanges.

This method is best suited to inspection of long, straight pipe runs (without flanges, connections and other joining pipework) which tend to be found more often on-shore than off-shore.

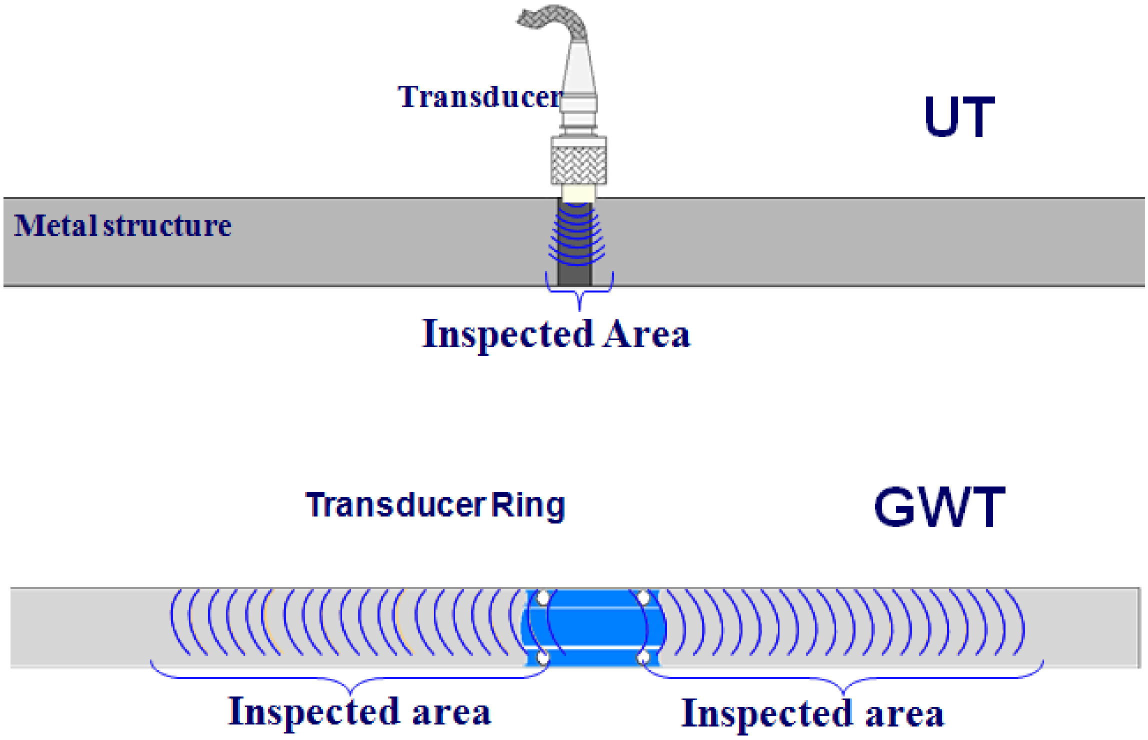


Figure A2-11: Operation of guided wave testing (GWT) compared with 0° pulse-echo UT (courtesy Guided Ultrasonics Limited).

A2.5.2 Overview of method

A Guided Wave system is composed of three primary components: the transducer ring, the instrument and a laptop computer running the controlling software. Figure A2-12 shows an example of use of an inflatable transducer ring, which needs to be attached directly to the pipe.

Figure A2-12: Equipment for GWT with inflatable sensor ring attached to an un-insulated section of pipe (courtesy Guided Ultrasonics Limited).

In general, little surface preparation is required (beyond removal of the insulation) because the operating frequency is relatively low; typically below 100 kHz. The transducer ring must be in contact with the surface of the pipe around the entire circumference of the pipe.

The transducer ring is attached, software settings selected, and measurements captured in a few minutes. In doing this the system performs a considerable amount of processing, including a range of self-checking procedures, calibration, and the recording of all measurements and settings.

The results are displayed in two formats: A-scan and C-scan. The A-scan (see Figure A2-13, lower plot) is the typical format used for GWT data representation in which the vertical axis shows the reflected amplitude (linear or logarithmic scale) and the horizontal axis represents distance from the transducer ring position.

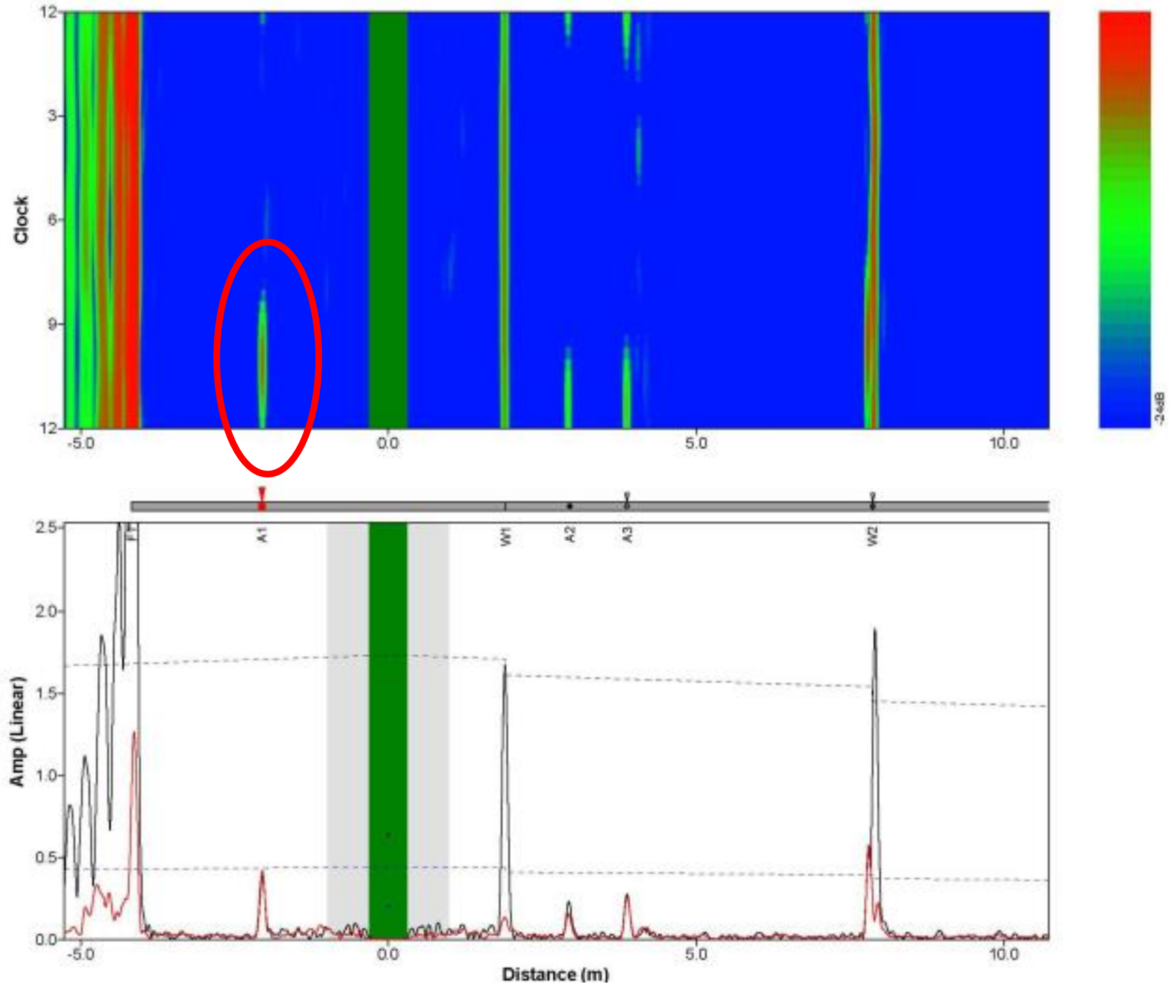


Figure A2-13: Example of GWT results, showing both the A-Scan type trace (below), and the C-Scan type unrolled pipe display (above). The weld W1 is a symmetric feature, extending around the entire circumference, whereas the defect A1 (circled in red) is non-symmetric and localized at the 9 – 12 o'clock position. The dashed curves are DAC curves (the upper curve is the weld DAC, lower curve the call DAC) (courtesy Guided Ultrasonics Limited).

The system is able to gather data separately for each direction along the pipe, so the results are plotted for both positive and negative distances from the transducer ring position. Indications of features or defects are given by reflected signals whose amplitude exceeds a threshold. Additionally, two different wave modes are used concurrently by the instrument, allowing it to differentiate defect reflections from those coming from axially symmetric reflectors such as butt welds.

The colour contour plot above the A-scan plot in Figure A2-13 is a C-scan map of the results, where the vertical axis is the angular position around the pipe circumference and the horizontal axis is distance. The purpose of the C-scan is to show the variation of the strengths of the reflections according to their location around the circumference of the pipe.

The C-scan images are calculated using separate signals from the transducer elements around the transducer ring and processed by imaging algorithms; they indicate the circumferential extent of defects and allow for focusing, thus helping to distinguish localised deep pits from spread-out general corrosion.

Testing is always done over a range of frequencies, which has minimal impact on inspection speed. This is important because the sensitivity to defects varies with frequency according to their dimensions, so a frequency sweep brings out the best sensitivity for each of any defects along the length being tested, thus increasing the POD; this also helps distinguishing defect reflections from reflections coming from regular geometric features.

The detection capability of GWT equipment is related to the loss of cross-sectional pipe wall area. Sensitivity is usually quoted as a percent of the total cross-sectional area of the (annular) pipe wall. When used as an inspection method, corrosion generating an area of wall loss representing a loss of ~5% or more of the pipe wall cross-sectional area can usually be detected reliably unless in close proximity to a weld or other geometric feature generating a GWT echo.

GWT can also be used as a permanently installed sensor system for continuous monitoring (e.g. the GUL gPIMS system). In this mode the sensitivity to wall loss is increased and changes in cross-sectional area at the 0.5 – 1% level can then be detected with high reliability on straight sections of pipe.

Since GWT is sensitive to loss of cross-sectional area, the through-wall extent required for the reflected signal to be above the detection threshold depends on the circumferential extent (and circumferential profile) of the corrosion.

For GWT detection, areas of wall loss that are circumferentially localised need to have greater wall loss than those that are more extended circumferentially, as illustrated in Figure A2-14. This plot shows, for an 8” sch 40 pipe, the wall loss needed for detection as a function of the detection threshold in % cross-sectional area change (CSC). The three curves show the wall losses detectable at the 0.5%, 1% and 5% CSC levels, assuming that the circumferential profile of the wall loss is elliptical (0.65 fill factor).

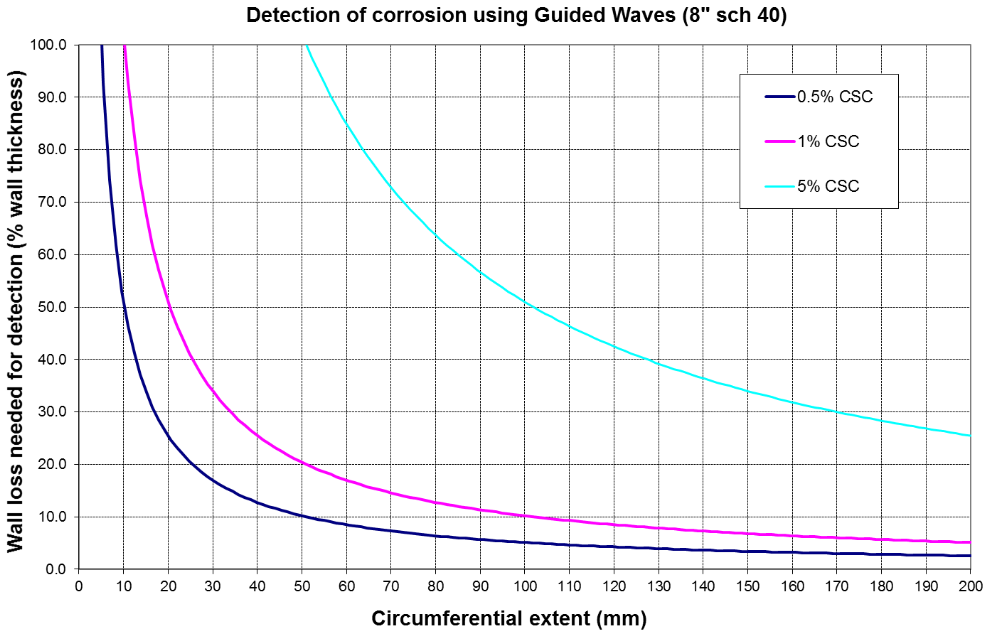


Figure A2-14: Curves showing the wall loss (as a % of wall thickness) needed for GWT detection as a function of circumferential extent. Three different curves are shown for different detection thresholds expressed in % cross sectional change (CSC), assuming that the circumferential profile of the wall loss is elliptical (0.65 fill factor).

In Figure A2-14, the curves show that an area of wall loss with a circumferential extent of 50mm needs to have wall losses of between 10% and 20% for detection at the 0.5% and 1% CSC levels respectively. However, if the detection threshold is 5% CSC, then a wall loss of 100% (i.e. through wall) is needed. For a circumferential extent of 100mm, the corresponding wall losses needed for detection are reduced by a factor two, so for a detection threshold of 5% CSC, a 50% wall loss flaw could be detected. Different results are obtained for different diameter pipes.

Figure A2-15 shows similar curves but these are more generally applicable as circumferential extent is plotted as a percentage of the pipe circumference. The results given in Figure A2-15 vary only slightly with pipe OD, unlike those given in Figure A2-14.

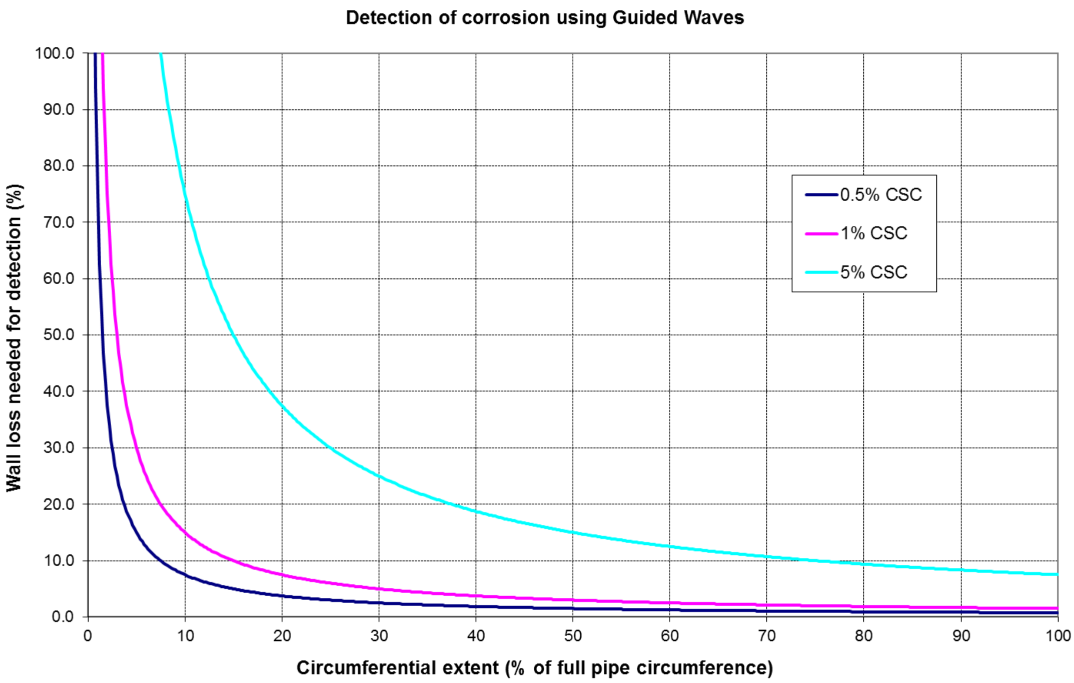


Figure A2-15: Curves showing the wall loss (as a % of wall thickness) needed for GWT detection as a function of circumferential extent as a % of the pipe circumference. Three different curves are shown for different detection thresholds expressed in % cross sectional change (CSC).

GWT is a screening method and, as such, does not provide quantitative information on the through-wall extent of the wall loss. The strength and circumferential localisation of the response from corrosion can however provide qualitative information on its severity.

Effective interpretation of the resulting GWT data involves a good understanding of the signals involved (including the different propagation modes) and can require considerable expertise and training.

A2.5.3 Application to CUI inspection

For GWT inspection of CUI, the insulation needs to be removed along a small section of the pipe to allow the GWT sensor ring to be attached directly to the pipe wall.

Infrequently, the coating also needs to be removed locally to the sensor ring to achieve sufficient coupling to the metal pipe surface.

Some coatings (especially bitumastic) and PFP materials that are bonded to the pipe can damp the propagation of guided waves and hence significantly reduce its effective range to only a few metres.

Nevertheless, the advantage of GWT is that it provides a rapid method for screening long lengths of pipe for CUI and other forms of degradation (both internal and external) provided they are not too localised circumferentially to fall below the detection threshold of the method.

An example of GWT data showing detection of significant CUI in a 4” pipe is given in Figure A2-16. This was verified following removal of the insulation which showed an extensive area of corrosion.

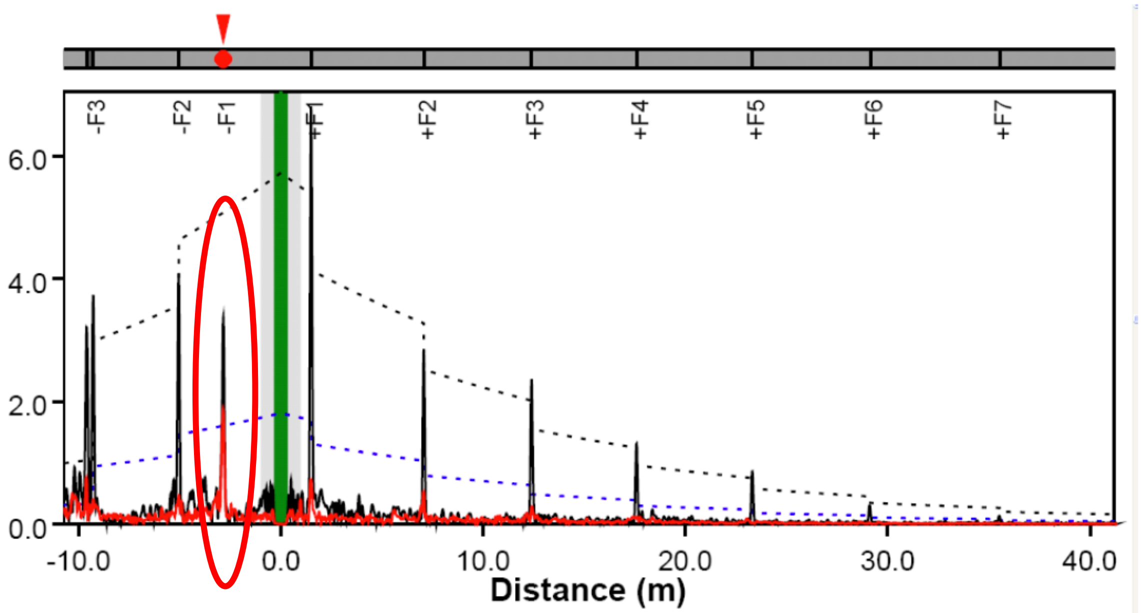


Figure A2-16: Example of GWT data showing (in red) CUI detected and verified in a 4" pipe (courtesy Guided Ultrasonics Limited).

A2.5.4 HOIS trial results

GWT was shortlisted as a CUI inspection method for trial/further investigation and two trials were performed, as follows.

The first trial was performed in the HOIS NICE facility and was based on two of the ex-service 10" pipes welded together with 100mm of Rockwool insulation and Ulvashield cladding. The sensor ring was attached close to each end of the pipe in turn, which were not insulated.

The results obtained correctly indicated that the test pipe was severely corroded, and numerous indications were found, which affected the overall propagation of guided waves along the pipe such that recognisable signals from the weld and pipe end were not seen. For this reason, the trial did not meet its original aim of providing POD information as a function of the severity of the individual corroded areas.

The second GWT trial was on a 3" sales gas line at an on-shore oil and gas facility. Of the 31 test locations inspected, for nine of these locations some “possible” concerns were raised with various comments. However selective stripping of the locations as identified in the GWT report did not take place due to logistical issues. Hence it was unclear how effective this GWT site trial was in identifying CUI.

For case studies describing site applications of GWT for inspection of CUI, see Section 8.4 and an overview of some successful GWT’s application for CUI see Section 8.3.

A2.5.5 Summary

Method:	**Guided wave testing method**
Basis:	Screening method looking for reflections from wall loss caused by CUI.
Strengths:	• Can cover long lengths of pipe runs in one measurement. • Applicable to wide range of pipe diameters and wall thicknesses • Sensitivity to loss of cross-sectional area can be assessed from data • Can be used for CUI monitoring at specific locations using a permanently installed sensor ring which gives greater sensitivity to CUI. • One of the most widely used NDT methods for CUI inspection, especially when assessed in terms of km of pipe inspected per year.
Limitations:	• Sensitive to loss of cross-sectional area, not % wall loss, so can miss circumferentially localised CUI, especially for larger diameter pipes. • Not applicable to vessels. • Advantages usually limited to long straight pipe runs and above ground pipelines. • Will not go through flanges. • Need to remove insulation to mount sensor ring on pipe. • Issues have arisen with data interpretation, and the competence/ training of operators.
Overall:	Significant usage in at least one geographical onshore area for CUI screening on long straight pipe runs (i.e. more at onshore locations than offshore). Generally, needs follow up with more local methods if indications found to confirm severity (e.g. radiography, removal of insulation).

A2.6 Radiographic methods

A2.6.1 Overview

There are various different approaches to industrial radiography for CUI inspection, based on different radiation sources and detectors.

All are based on the penetrating “power” of ionising radiation to see through the insulation and cladding to provide information on the condition of the underlying steel component within. The radiography methods described in the present section require the source and detector to be positioned on opposite sides of the component, so that the radiation is transmitted through the component, or at least the insulation, with varying amounts of attenuation.

For CUI inspection, where the radiation attenuation caused by the insulation and cladding is relatively low, a number of manually deployed, real-time X-ray devices are sometimes used, especially in the USA. Although these use much lower energy and power radiation sources than conventional radiography, their deployment in the UK must be in accordance with IRR17.

Further information is now given on the various different radiographic methods for CUI inspection.

Conventional radiography for CUI (both film and digital) should be performed in accordance with the international standards ISO 20769: Parts 1 and 2 (see also the HOIS RP for in-service digital radiography Burch, 2015).

A2.6.2 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. The photon energy spectra generated by these sources are shown in Figure A2-17. 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 which can be used for through-wall sizing of CUI. 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.

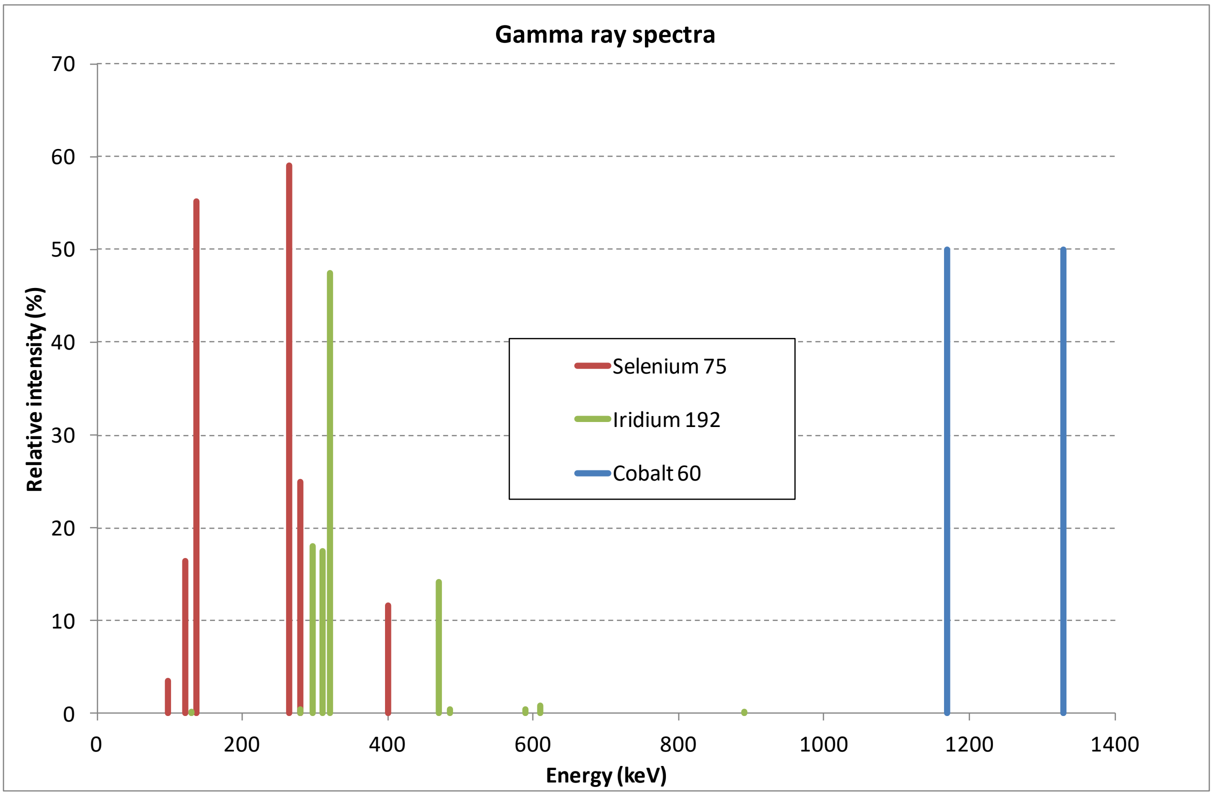


Figure A2-17: Energy spectra of the different isotope sources used for industrial radiography.

Portable X-ray sources (some are battery powered and pulsed) are occasionally used for in-service inspection but are generally less penetrating than Se 75 and can be fragile.

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. However careful consideration of personnel protection and shielding from the effects of ionising radiation during exposures is needed, especially on a relatively compact installation such as an offshore rig.

A2.6.3 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.

Linear Detector Arrays (LDA's)
Linear X-ray sensitive real-time detector arrays are also available. With these the image is built up by scanning the source and detector in a direction perpendicular to the axis of the array.

Within the field of in-service inspection for CUI, 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 (DDA's). 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. This can help to make the method more attractive for CUI inspection which often needs high coverage. 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.

Incorporation of a DDA (or linear detector arrays - LDA) into an automated scanning system allows much higher coverages to be obtained for those components (e.g. long straight pipe runs without bends, tees, branches etc.) that can be inspected with such a device.

A2.6.4 Double-wall double image/tangential radiography

Outline of method

The overall configuration of source and detector for double wall double image radiography (DWDI), combined with tangential (sometimes called profile) radiography, is shown in Figure A2-18. The radiation source is well removed (stood-off) from one pipe wall and the straight detector is positioned on the opposite side of the pipe, generally in contact with the insulation/cladding or as close as possible to it.

The advantage of tangential radiography is that a direct 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 a steel pipe wall is given by

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

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), including any additional attenuation caused by the insulation and metallic cladding. Note that wet insulation can cause significant radiation attenuation.

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 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.

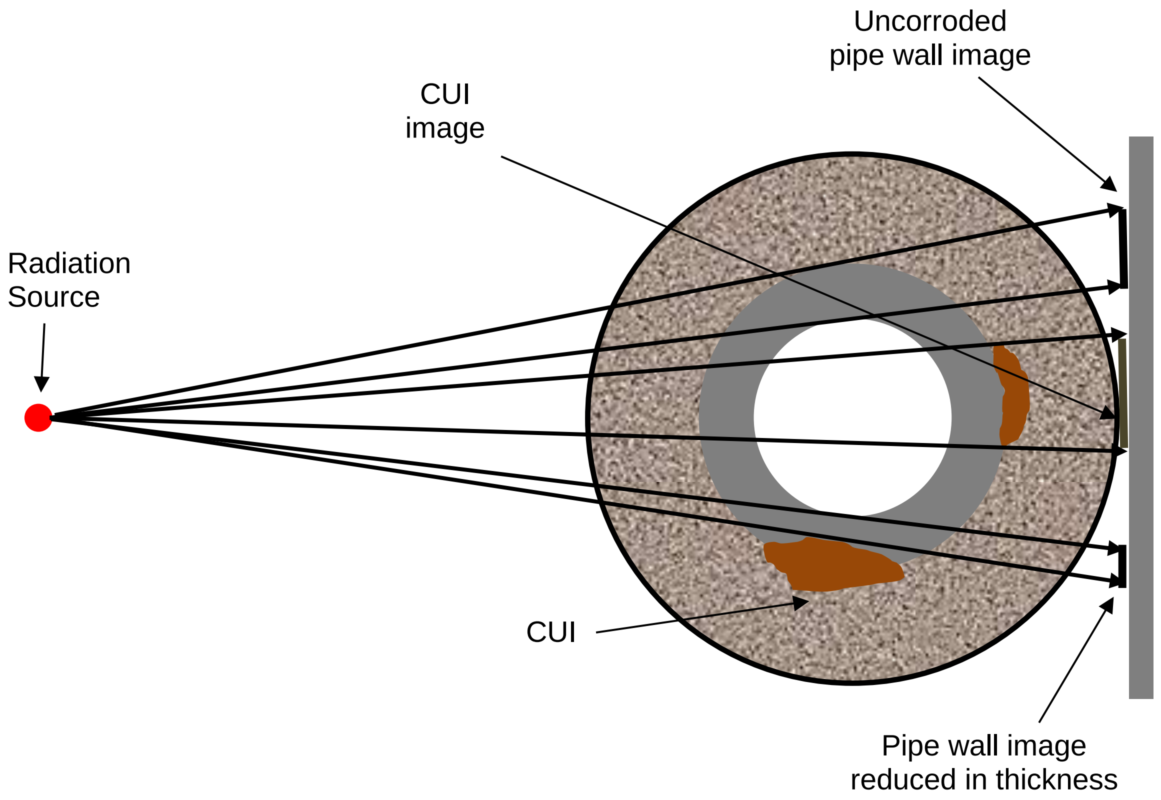


Figure A2-18: Schematic of combined double-wall double image (DWDI) and tangential radiography for CUI inspection.

The reliability of the measurements of remaining ligament obtained with tangential radiography can be affected by the morphology of the corrosion (Burch, 2015; ISO 20769-1). Reliable sizing is usually only obtained for extended area of corrosion, without localised pitting. If localised pitting is present then the measurements are potentially unreliable.

If the external corrosion is not present at the tangent position, it may be detected between the two tangent positions by its effect on the image density (or grey levels in a digital image) using DWDI. DWDI can be applied to larger diameter/thicker walled pipes than tangential radiography. DWDI does not provide a quantitative measurement of the through wall extent of the wall loss.

An important caveat for DWDI is that the presence of associated corrosion product will reduce the overall contrast of the corroded area, making it more difficult to detect reliably. In practice the only indication of CUI in these circumstance may be imaging of the irregularities that can form in corrosion product (including linear features that appear to be crack-like).

For larger diameter/wall thickness pipes with maximum tangential paths too high for full tangential radiography, the radiographs can still show the presence of CUI at the tangent position through the associated corrosion product that will create a bulge in the pipe wall profile (see Figure A2-19). If the corrosion product is not present, then the wall loss may show as a depression in the pipe wall profile, depending on its profile. Determination of the remaining ligament is not however possible as the position of the inner diameter will not be visible on the radiograph.

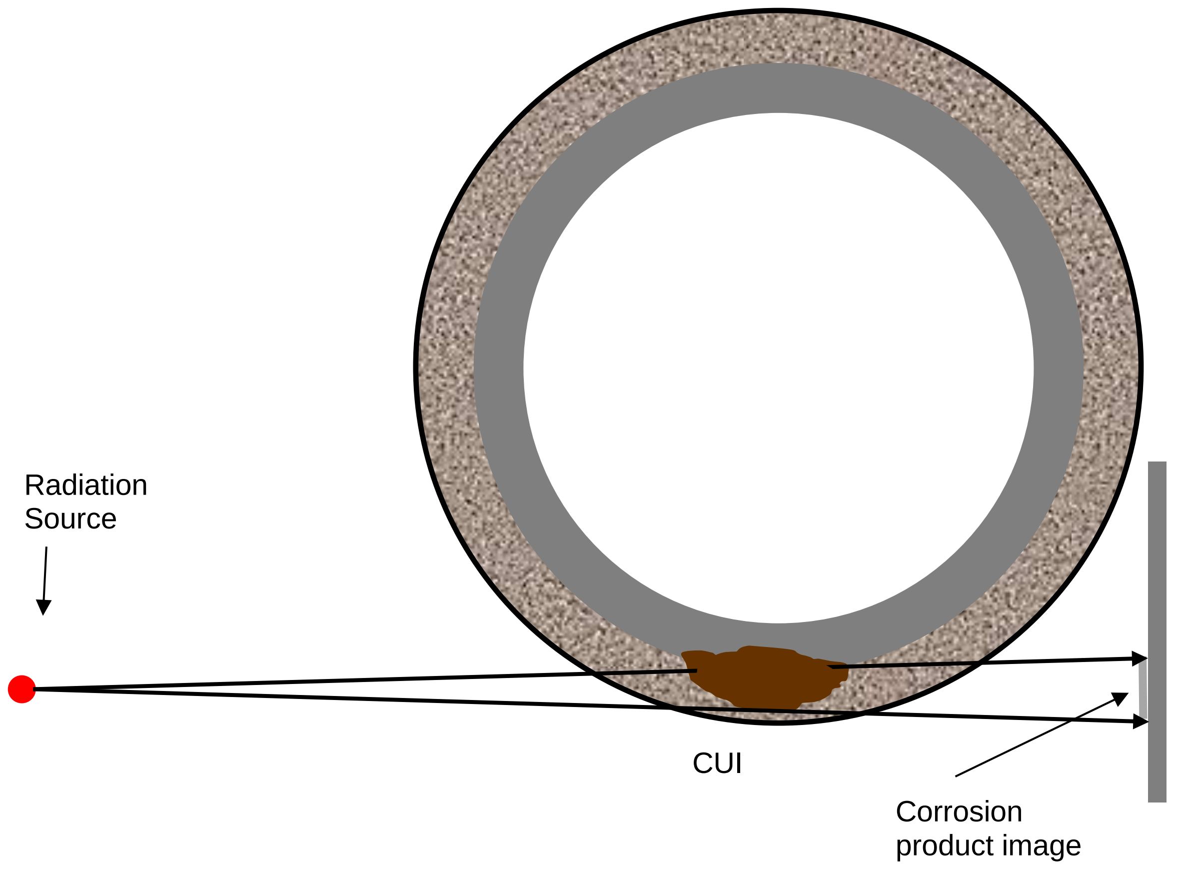


Figure A2-19: Schematic of radiography of large diameter pipe showing image of pipe wall OD profile and any corrosion product associated with CUI.

With tangential/DWDI 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 DDAs instead of film allows 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).

Application to CUI

Examples of computed radiography DWDI/tangential images showing CUI are given in Figure A2-20 (pipe bend) and Figure A2-21 (near to a tee joint). Note that in both cases the wall loss can be clearly seen, together with the in-situ corrosion product.

In service inspection of insulated pipes using radiography is covered by the standards ISO 20769 Parts 1 and 2 and a HOIS RP (Burch, 2015). Any radiography for CUI inspection should be performed in accordance with these documents.

The main advantage of DWDI/tangential radiography for CUI 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 ISO 20769-1 and Burch (2015).

Note however the caveats on sizing of external corrosion, with or without insulation contained in the HOIS safety notice on this topic (Burch, 2014) and in ISO 20769. This shows that for some corrosion morphologies (mainly those with localised circumferential extents) significant under-estimates of the wall loss are likely to be obtained when using tangential radiography.

As this is a relatively slow method, it is not applicable for the detection of CUI over large areas of pipework, unless used in an automated scanner.

Conventional tangential radiography can however provide information on the severity of the corrosion, once it has been located by another screening method. Alternatively, DWDI/tangential RT can be used as a sampling method to inspect limited areas where there is a high probability of CUI occurrence. Its ability to inspect bends, tees and other complex geometries is particularly valuable.

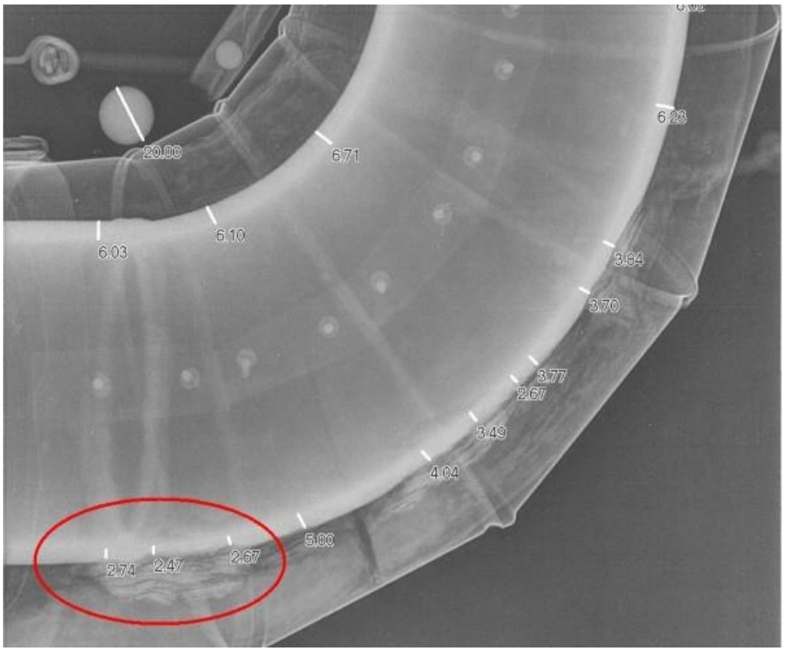


Figure A2-20: Example of combined double-wall double image and tangential radiography showing an area of CUI on a pipe bend (outlined in red), courtesy Oceaneering Ltd.

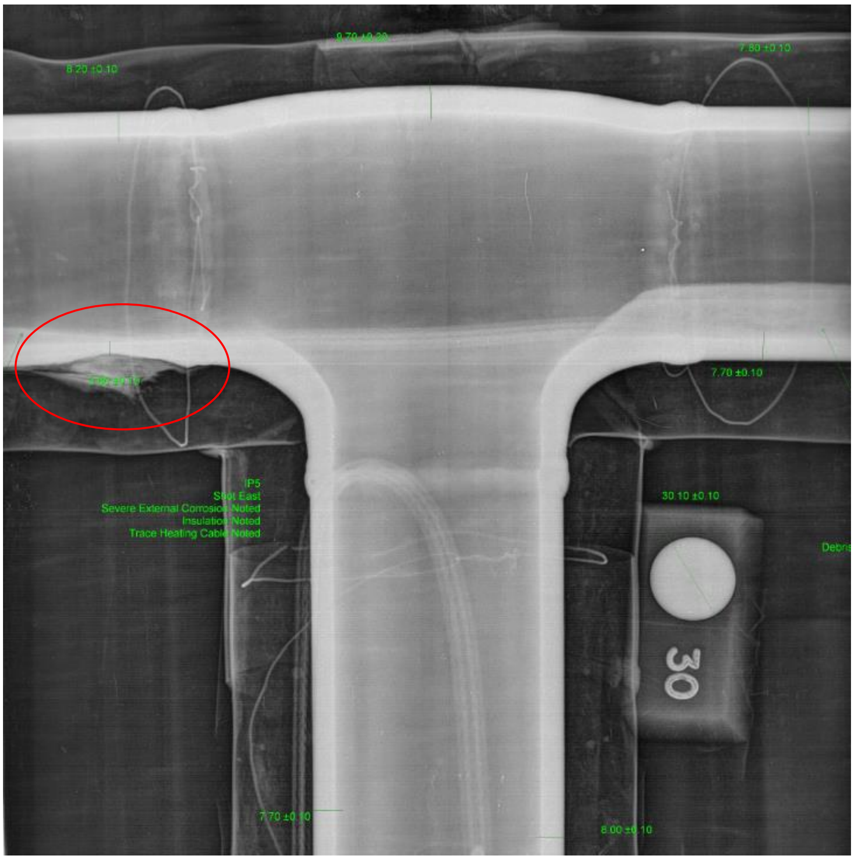


Figure A2-21: Example of combined double-wall double image and tangential radiography showing an area of CUI near a pipe tee joint (outlined in red), courtesy EM&I.

A DWDI CR image of external corrosion in a 6" sch 40 pipe close to the beam axis is shown in Figure A2-22. [In this case, the pipe was not insulated, but the image would have been very similar if insulation had been present]. In this example, the overall contrast of the corrosion was substantially reduced due to the additional attenuation caused by the corrosion product, despite the steel wall loss being up to around 75%.

Any attempts to estimate the extent of the wall loss from DWDI images by analysis of the image grey levels will give substantial underestimates due to the "infilling" effects of the corrosion product. Indeed, the additional attenuation caused by the corrosion product may exceed the reduction in attenuation caused by the loss of steel, giving an overall increase in attenuation instead of the reduction that would be obtained without corrosion product being present.

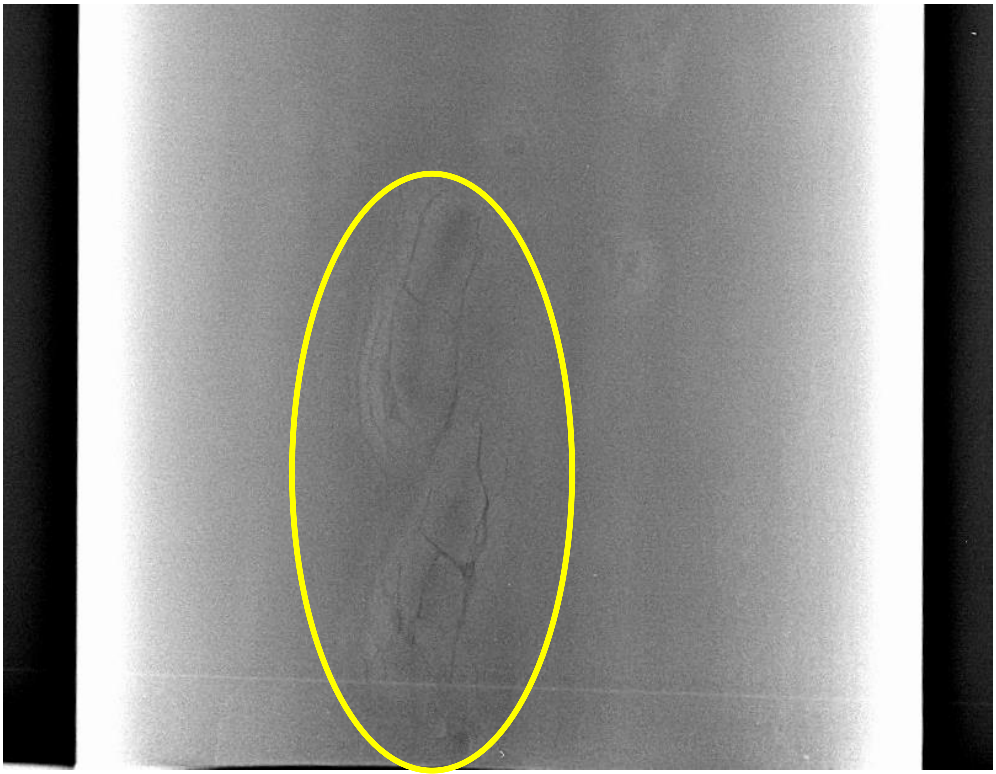


Figure A2-22: DWDI image showing presence of external corrosion and associated corrosion product – note the overall low contrast despite the wall loss due to the corrosion being about 75% of the wall thickness, caused by the "infilling" effect of the corrosion product.

HOIS trial results

In the first set of HOIS CUI trials (Burch and Kitchener, 2016), a limited site trial was carried out using flash radiography equipment to perform tangential radiography. The radiation source was a pulsed X-ray unit, and the detector was a DDA.

This limited trial has shown that the flash radiography method is a promising method for CUI inspection, capable of providing clear images (see example given Figure A2-23) of known corrosion under insulation on small bore (3") pipework (without corrosion product). This trial did not however provide any POD information on sensitivity to small amounts of corrosion.

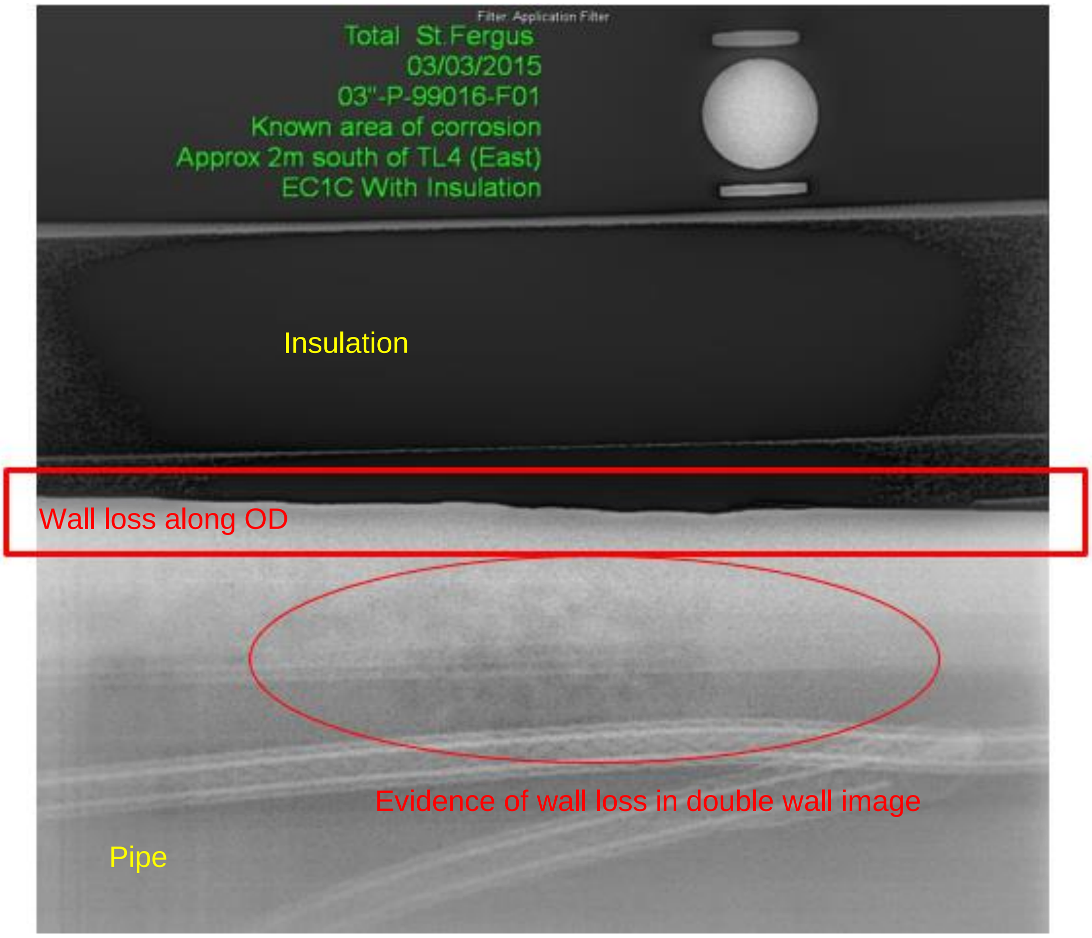


Figure A2-23: An image of CUI taken with the flash radiography method. The corrosion can be seen within the red areas. The rectangular area shows clear corrosion on the edge of the pipe; the ellipse surrounds a darker, speckled area indicative of corrosion.

The second set of HOIS/OGTC trials (Burch and Collett, 2019), a semi-blind digital radiography trial was performed by Acuren on ex-service small-bore pipes with areas of wall loss mostly having corrosion product still in place. An Ir 192 source and a Digital Detector Array (DD)A were used for this trial which was performed in a radiation bay.

The resulting radiographs had high resolution and high signal to noise ratio. These clearly showed the corrosion product material outside the pipe OD in the tangential portion of the images, where the wall loss due to CUI was also visible. Within the central DWDI sections of the pipe radiographs the CUI was only visible by the structure in the corrosion product which varied depending on the severity of the corrosion. Some areas of moisture in the insulation were also visible.

In this trial. all the areas of CUI were correctly located with no false calls (i.e. a corrosion hit rate of 100%).

As an example, in Figure A2-24, two areas of CUI are highlighted. For both, the external corrosion product and external wall loss can be clearly seen. This radiograph was also centred on an area of wet insulation which can be seen to have caused additional radiation attenuation where it was present – indicated by the red dashed vertical lines.

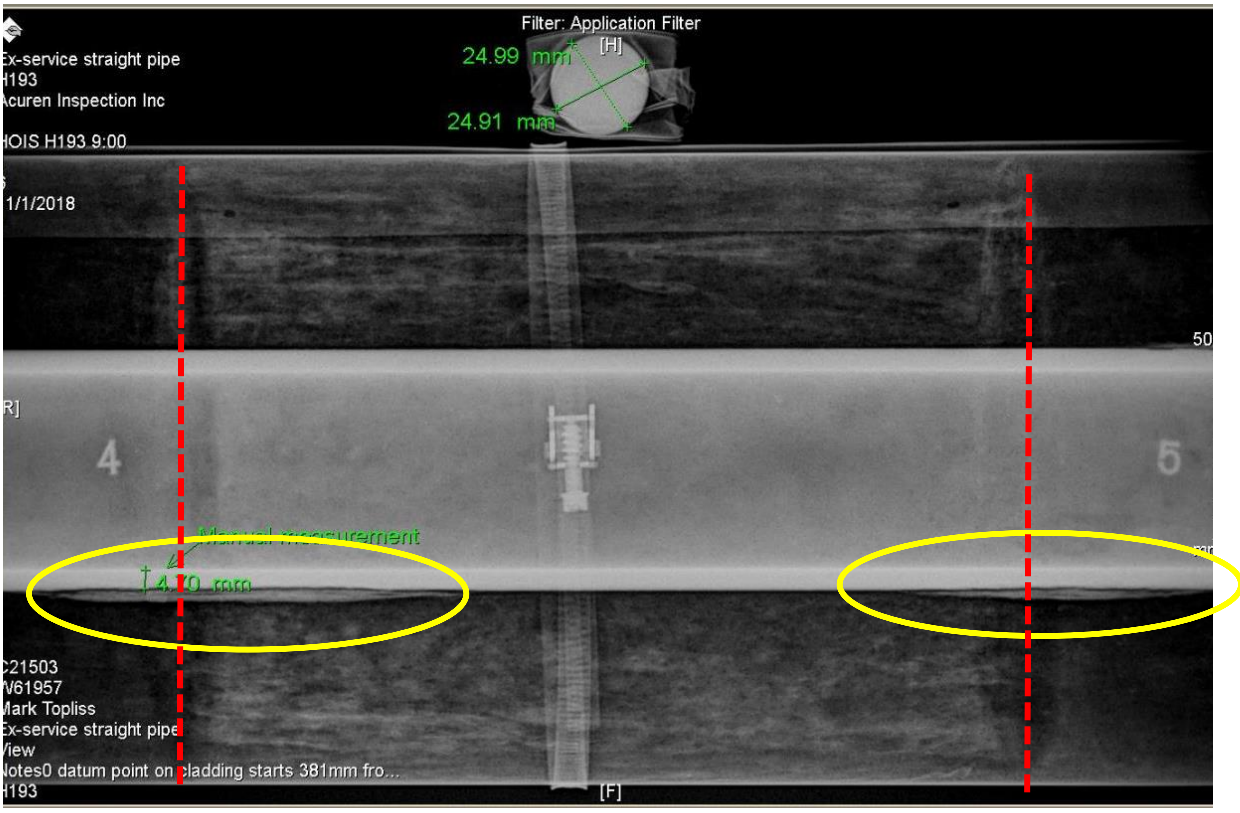


Figure A2-24: Digital radiograph obtained with an Ir 192 source and DDA. Two areas of CUI are highlighted and the extent of a wet section of insulation is indicated by the red vertical lines.

Summary

Method:	**Combined DWDI and tangential radiography to detect CUI and 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:	• Quantitative (with some caveats) wall thickness measurements using the tangential method. • Applicable to changes in geometry (bends, reducers, tees etc.). • Can detect CUI using double wall methods in larger diameter/wall thickness pipes, provided the total penetrated thickness through the component is less than about 100mm steel equivalent thickness, (including pipe wall, insulation and liquid product if present), when using Ir 192, although the radiographic contrast of the CUI will be substantially reduced by any corrosion product present. • Can be deployed in an automated scanning system to rapidly inspect certain circumferential positions (e.g. 6 o'clock) for CUI.
Limitations:	• Radiation safety issues

	• Normally slow and limited to sampling inspections or follow up from other methods (e.g. GWT) unless deployed as part of an automated scanning system • 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. • Limited application to vessels
Overall:	Quite widely used for CUI inspection of smaller bore pipes, but slow (typically 1 image per hour in site conditions, including setup time). Best suited to sampling inspection or follow up of suspect areas identified by other methods. Automated scanners are used for rapid inspection of CUI at a single circumferential location (6 o'clock) on long above ground pipe runs/pipelines in remote locations.

A2.6.5 Double-wall single image radiography

Outline of method
The overall configuration of source and detector for double wall single image radiography (DWSI), is shown in Figure A2-25. The source is positioned close to one pipe wall, and the detector is usually wrapped around the opposite side (for CUI the detector would need to be positioned on the outside of the insulation). This technique is generally used for larger diameter/wall thickness pipes than DWDI/tangential radiography.

CUI 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.

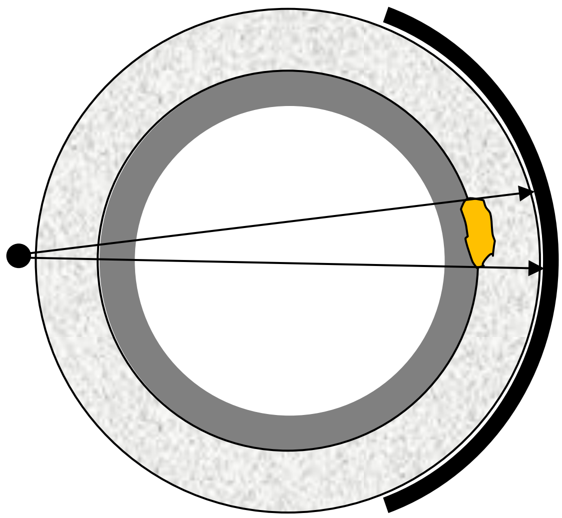


Figure A2-25: Schematic of double-wall single image radiography for CUI inspection.

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.

Application to CUI
DWSI is less commonly applied than DWDI/tangential radiography for CUI inspection as it does not provide information on the through-wall extent of any degradation. It can however be applied to larger diameter and thicker wall thickness pipes than tangential radiography.

Summary

Method:	**Double wall single image radiography to find CUI by changes in image density/grey level using either film or imaging plate (IP/CR).**
Basis:	Areas of CUI can be seen on radiographs, even in the presence of corrosion product, although this reduces their contrast
Strengths:	• Applicable to larger diameter pipes than DWDI/tangential • Applicable to some changes in geometry (bends, reducers etc.).
Limitations:	• Radiation safety issues • Slow • Not applicable to vessels. • Affected by presence of liquid product • Contrast of CUI reduced by corrosion product if present (may even be reversed) • Less widely used for CUI inspection than tangential radiography
Overall:	A slow method for finding CUI in pipes with diameters/wall thicknesses larger than is possible for DWDI/tangential RT, but not able to quantify the wall loss.

A2.6.6 Real-time imaging radiography

Outline of method and application to CUI inspection
Manually deployed systems for real-time radiography are used, particularly in the USA, for CUI inspection. These feature a low energy radiation source (either a gamma-ray source or a low power X-ray source) and a real-time detector, mounted on a C-arm. A schematic of this method is shown in Figure A2-26, and an example of its application to CUI inspection is shown in Figure A2-27.

The Sentinel OpenVision system includes a low power X-ray source up to 70kV, whereas a similar device from Lixi (Gadscope) uses a Gadolinium 153 isotope source.

The use of these unshielded manually deployed devices raises some significant safety issues. It is important to monitor the radiation outputs from these devices using a monitor intended for the comparatively low energy radiation they emit. The radiation levels can be very localised around the devices so it is important to monitor all key areas.

In the UK, ensuring compliance with the legal requirements of the IRR17 is required. This may require equipment modifications (source collimator) and/or radiation PPE (lead lined coat etc.). Usage in the UK for routine CUI inspection is limited. However, in the USA and elsewhere, where the regulations for usage of ionising radiations are different, they are much more widely used.

The radiation source is generally too weak to penetrate the pipe wall, but the external profile of the pipe wall can be inspected for wall loss due to corrosion and/or build-up of corrosion product. Hence provided the corrosion is at the tangent position its presence can be detected. It is unlikely that this method will be capable of providing a quantitative measurement of wall loss.

These devices can also be used to find wet insulation, which attenuates radiation much more strongly than dry insulation. It is possible that wet insulation would reduce the capability of the device to detect CUI underneath it, as the radiation may fail to penetrate the wet insulation.

Being manually deployed, this method is much faster than traditional film or digital radiography described in Appendix A2.6.4 and Appendix A2.6.5, as the setup is greatly reduced and the exposure time is negligible.

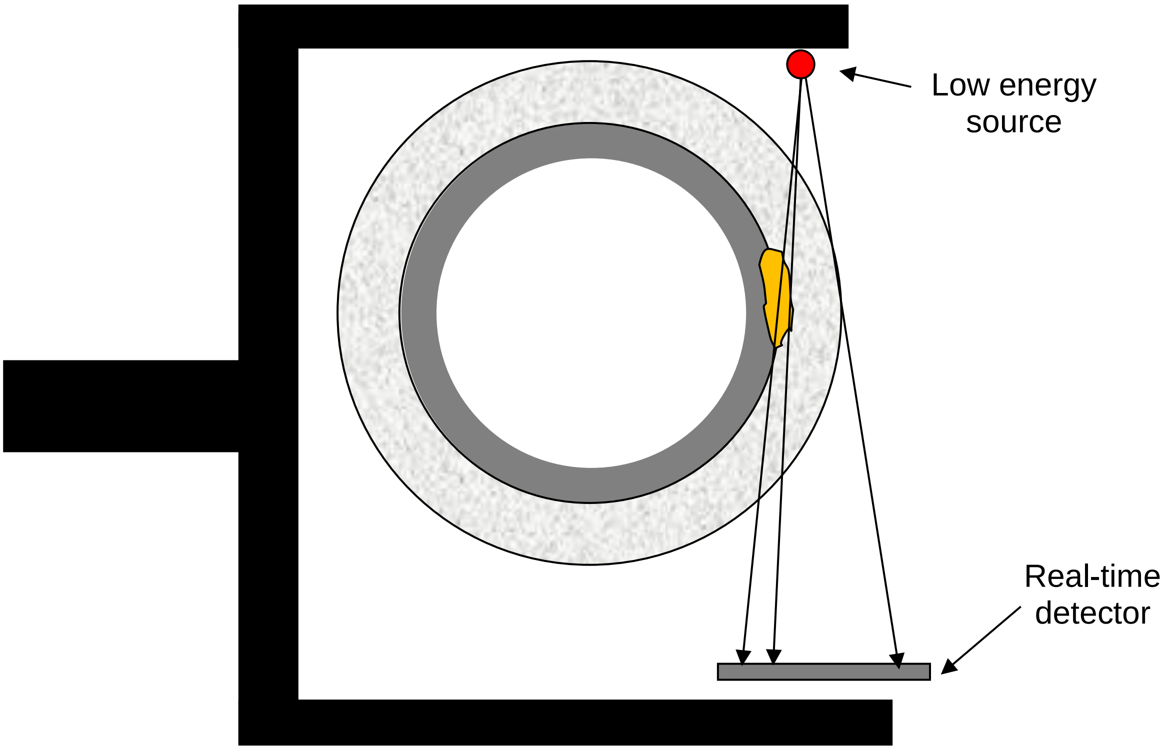


Figure A2-26: Schematic of real time radiography for CUI inspection.

Figure A2-27: The Sentinel OpenVision real time radiography equipment being used for CUI inspection (courtesy TUV Petrochem).

Figure A2-28 gives an OpenVision RTR image which is said to show CUI. However, there is no evidence of any corrosion product in this image.

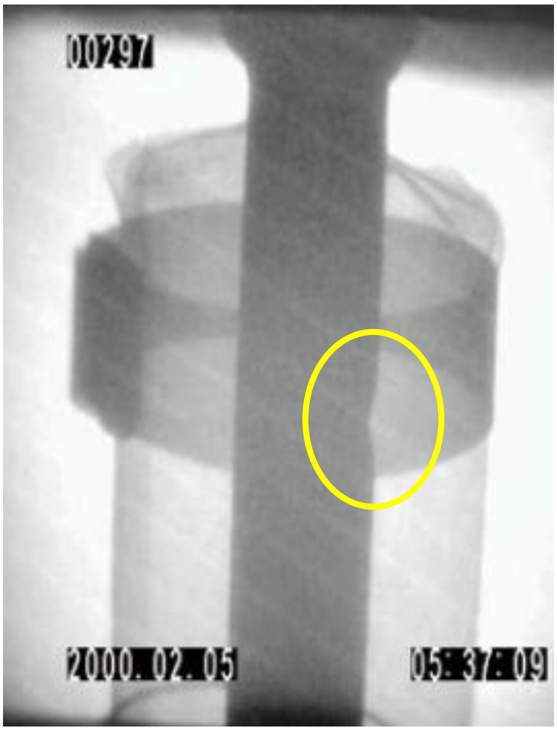


Figure A2-28: Example of OpenVision radiographic image said to show CUI (courtesy TUV Petrochem).

HOIS trials

In the first set of HOIS CUI trials (Burch and Kitchener, 2016), open trials in a radiation bay performed with an OpenVision RTR unit gave images that indicated the presence of CUI with and without corrosion product.

The second set of HOIS/OGTC trials (Burch and Collett, 2019), included a blind OpenVision trial on ex-service small-bore pipes with areas of wall loss mostly having corrosion product still in place. The OpenVision unit had a source collimator fitted to reduce the X-ray dosage to the operator.

Almost 80% of the corroded areas were correctly reported by the OpenVision trial, although the axial extents of the reported areas were substantially less than those actually present. Hence this method was only showing sections of the corrosion, not their full extent. Two corroded areas were missed by the OpenVision trial. There were also two false CUI calls and other features reported, such as saw cuts, that were not present when the pipe was visually inspected.

Three of the four sections of insulation that had been wetted were not reported. One of these areas was definitely wet at the time of the trial, but the other two may possibly have dried out by the time of the trial. There was one wet area reported that did not correspond to the known locations of moisture in the insulation.

The frame grab images shown in the trial results had limited signal to noise ratio and spatial resolution, although the recorded videos were substantially clearer. The features reported by the trial participant in some of them were difficult to discern to the untrained eye without reference to the video sequences.

Summary

Method:	**Handheld C-arm device based on a low strength radiation source (gamma or X–ray) and an imaging detector**
Basis:	Aims to detect wet insulation and/or presence of external loss of wall and/or corrosion product by their effects on the pipe OD profile ("silhouette").
Strengths:	• Faster than conventional and digital radiography with no setup time. • Applicable to some changes in geometry (bends, reducers etc.). • Can detect CUI with or without corrosion product • Used quite widely in certain geographical areas (e.g. USA).
Limitations:	• Needs to comply with IRR17 in the UK. • Images may be noisy and difficult to interpret • Can be limited by space needed around the piping (e.g. pipes in racks) • For detection, the CUI must be tangential to the radiation beam. If a scan is performed only along the 6 o'clock position, CUI will be missed if it is confined to other circumferential locations. • Ability to detect CUI under wet insulation not proven. • Reliability for detection of wet insulation not fully confirmed in limited trial
Overall:	Can provide rapid, direct detection of CUI, provided limitations appreciated/safety issues addressed. Used in USA with reports of good results.

A2.6.7 Real-time profile radiography

Outline of method and application to CUI inspection
The Lixi Profiler shown in Figure A2-29 is a real-time C-arm based device similar to the real-time imaging systems described in Appendix A2.6.6. However, this device has only a single detector, not an imaging system. Thus, at any position, only a single measurement of radiation attenuation is made. As the unit is scanned along the component, a computer is used to build up a profile of the radiation attenuation. This shows how the attenuation varies as the device is moved manually, but there are no encoders or other means to quantify the measurement positions.

This device is much more sensitive than the real-time imaging systems and information can be obtained on the attenuation through both pipe walls and the insulation on both sides of the pipe.

The use of this unshielded manually deployed device raises similar safety issues to those of the real-time imaging systems described in Appendix A2.6.6, although the levels of radiation emitted are substantially lower than for the X-ray based Open Vision device. In the UK, it would need to operate in accordance with IRR17.

In the absence of corrosion product, this method can give an indication of the through-wall extent of any CUI present although ensuring complete coverage would be challenging in a site environment.

The total steel equivalent penetrated thickness that can be inspected with full sensitivity with this device is ~30mm (i.e. a wall thickness of 15mm, less if there is liquid product in the pipe).

Figure A2-29: Lixi profiler.

The Lixi profiler was evaluated as part of the CRIS POD trials and achieved a high overall POD for 6" NB pipes, with nominal wall thicknesses of 7.1 and 14.3mm (Burch and Hood, 2011). However, although the flaws in the test specimens in this trial were external and surrounded by insulation, there was no corrosion product in-situ.

For CUI it is generally understood that the corrosion product generated by the CUI stays in place, trapped by the insulation. If the corrosion product is still in place, then the reduced attenuation due to the loss of steel is compensated for by the increased attenuation through the corrosion product (put simply there is nowhere for the heavy iron atoms to go). Indeed, the attenuation may even be increased by the additional oxygen that gets combined with the iron to form various iron oxides. Hence with CUI, measuring the total radiation attenuation through the pipe is unlikely to provide an effective method for detection, unless the corrosion product has disappeared.

The Lixi profiler measures the total radiation attenuation through the complete insulated pipe and will therefore be affected by the presence of moisture in the insulation which will give higher attenuation than dry insulation. Hence wet insulation could mask associated CUI.

Summary

Method:	**Handheld device based on a low strength radiation source (gamma or X–ray) and a single detector**
Basis:	Radiation penetrates both pipe walls and the insulation/cladding. Attempts to detect CUI by reduction in total attenuation of radiation beam due to steel wall loss.
Strengths:	• Faster than conventional and digital radiography – real-time measurement of attenuation • Applicable to some changes in geometry (bends, reducers etc.). • Quantitative measurements of wall loss if corrosion product not present.
Limitations:	• If the corrosion product is present, the total radiation attenuation is unlikely to be significantly reduced (it may even be increased) so the POD for CUI may be low. • Wet insulation will give increased attenuation and may mask CUI at same location. • Radiation safety issues - manual, handheld device although the level of radiation emitted is much less than for the comparable OpenVision device. • Can be limited by space needed around the piping (e.g. pipes in racks) • Limited coverage • Not an imaging device
Overall:	Some usage for CUI inspection but likely to be unreliable due to presence of corrosion product and water in insulation both of which increase the attenuation measured by the device and would render it insensitive to steel wall loss.

A2.7 Pulsed eddy currents

A2.7.1 Introduction

For CUI inspection, the pulsed eddy current (PEC) sensor is arranged on the outside of the insulated pipe, with the aim of detecting directly any large-scale loss of wall thickness within the sensor footprint, directly beneath the sensor, as illustrated in Figure A2-30.

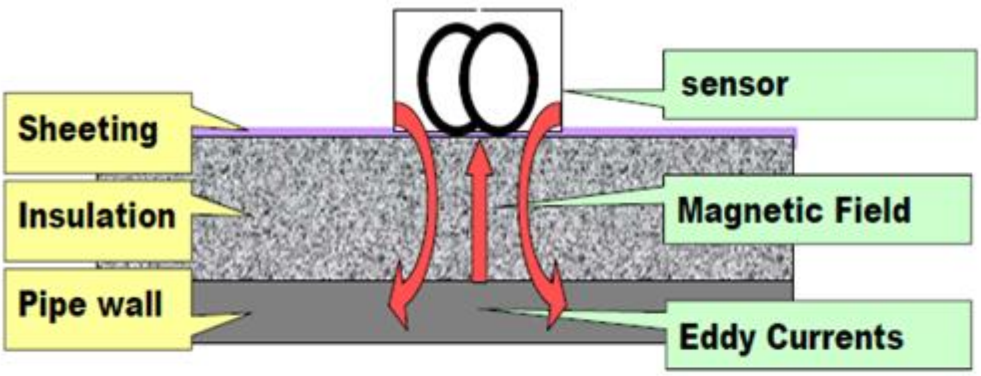


Figure A2-30: Principle of the pulsed eddy current method for CUI inspection (illustration courtesy of ApplusRTD).

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

Until recently, pulsed eddy current probes needed to be operated in a stop/start mode with the sensor stationary for the measurement period, the duration of which increases with the component wall thickness.

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 Rheinland Sonovation – Sonopec
- Maxwell NDT - PECT

The Eddyfi Lyft system has the capability of being able to continuously scan a component, although this is not practical for larger wall thickness components for which the measurement time at each probe position is higher. In addition, an array of PEC sensors is now available from Eddyfi (PECA™) and was included in the HOIS/OGTC trials in 2018/19 (Burch and Collett, 2019).

The original Shell PEC technology has now been adopted by TUV Rheinland Sonovation, and updated software has been developed. Improved probes and an array system were under development in Autumn 2019. The ability to continuously scan is now (December 2020) said to be available but none of these improvements were assessed during the 2018/19 HOIS/OGTC trials.

Maxwell NDT also offer an updated PEC system, with different electronics and probes. An array system is also said to be available, but was not assessed in the HOIS/OGTC trials.

A2.7.2 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 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.

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 then 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, as illustrated in Figure A2-31.

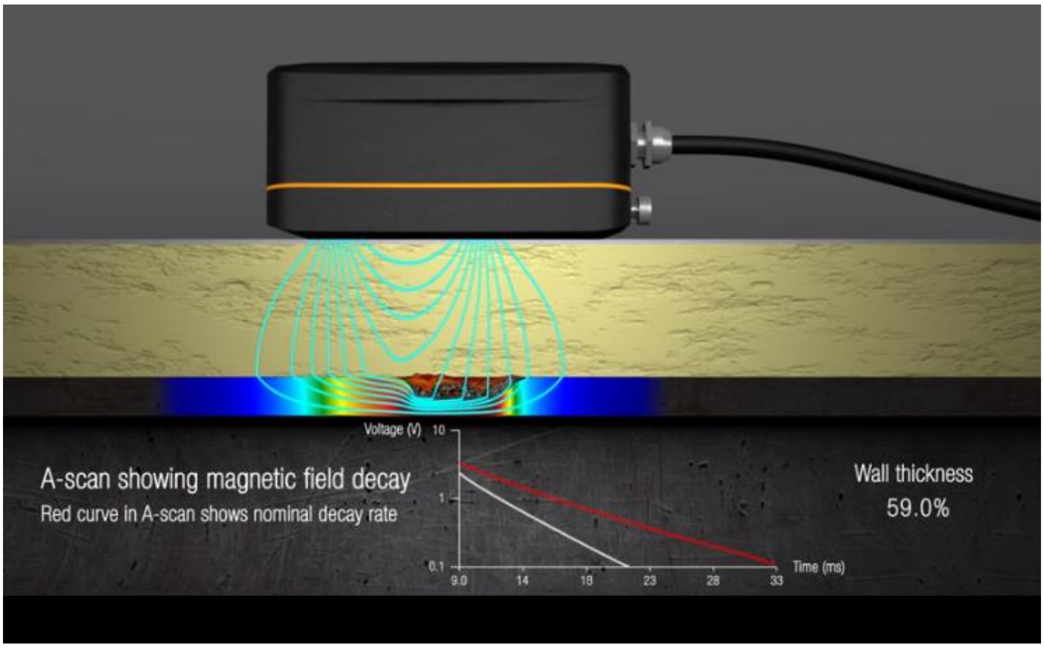


Figure A2-31: Pulsed eddy current inspection of an area of wall loss (illustration courtesy of Eddyfi).

The measured signal is usually shown on a plot in which the horizontal axis represents the time in milliseconds and the vertical axis the logarithm of the measured signal amplitude. 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 opposite object side and then 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):

$\tau = \mu\sigma\, d^2$.

Calibration methods are used to find the unknown variables in this equation (μσ), allowing a relative measurement of the object average thickness 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.

Examples of equipment for pulsed eddy current inspection are shown in Figure A2-32.

(a) (b)

(c)

Figure A2-32: Equipment for pulsed eddy current inspection: (a) Lyft (courtesy of Eddyfi), (b) Sonopec (courtesy of TUV Rheinland Sonovation) and (c) PECT (courtesy of Maxwell NDT)

A notable recent development has been the introduction of PEC arrays which comprise multiple PEC sensors arranged side by side. If the sensors can be operated simultaneously, instead of sequentially, significantly improved coverage rates can be achieved compared with single PEC probe systems. An example of a PEC array is shown in Figure A2-33

(a) (b) (c)

Figure A2-33: Examples of PEC equipment being operated in the 2018/19 HOIS/OGTC CUI trials: (a) Eddyfi Lyft PECA™ array, (b) TUV Rheinland Sonovation Sonopec and (c) Maxwell NDT PECT.

A2.7.3 Application to CUI inspection

For inspection through insulation, the pulsed eddy current sensor size needs to be similar to the insulation thickness, and the effective sensor footprint size will then be larger than the insulation thickness. At any one point, the sensor provides a measurement of wall loss, 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. Smaller scale pitting may either be not detected or undersized.

The time taken for a point measurement varies depending on the wall thickness 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.

With all PEC systems, the speed of scanning and coverage rates depends on wall thickness, with the speed decreasing as the wall thickness increases. In the recent HOIS/OGTC trials (Burch and Collett, 2019), varying scan speeds were found depending on the equipment used and the pipe wall thickness. The highest coverage rates were found with the Eddyfi PECA™ array and these varied from 13 (m^2/hr) for the sch 20 (6.4mm nominal wall thickness pipes) to

5 (m²/hr) for the sch 80 (15mm nominal wall thickness pipes). The lowest coverage rates were for single PEC probes on the sch 80 pipes (down to about 2 m²/hr).

For CUI inspection, the method can be adversely affected by outer metallic claddings on insulated pipes, depending on its material and also any metal within the insulation itself. Ferromagnetic cladding materials (e.g. galvanised steel, Aluzinc) have the greatest adverse effects on PEC. Non ferromagnetic cladding materials (e.g. stainless steel and aluminium) have much smaller effects, while more modern non-metallic claddings (e.g. Ulvashield) have no significant effect.

In addition, any corrosion product present associated with CUI may have the effect of reducing the loss of wall thickness measured by this method (i.e. non conservative under-estimation of the severity of the CUI) although this did not appear to be a significant issue in the HOIS CUI trials (Burch and Kitchener, 2016; Burch and Collett, 2019).

An example of pulsed eddy current data is given in Figure A2-34 taken from an insulated 10" sch 20 stainless steel pipe with 50mm of insulation and a nominal wall thickness of 6.4mm. The locations of six areas of CNC machined wall loss are marked on the scans. Some smaller areas of wall loss, present in this scan area, were not reported.

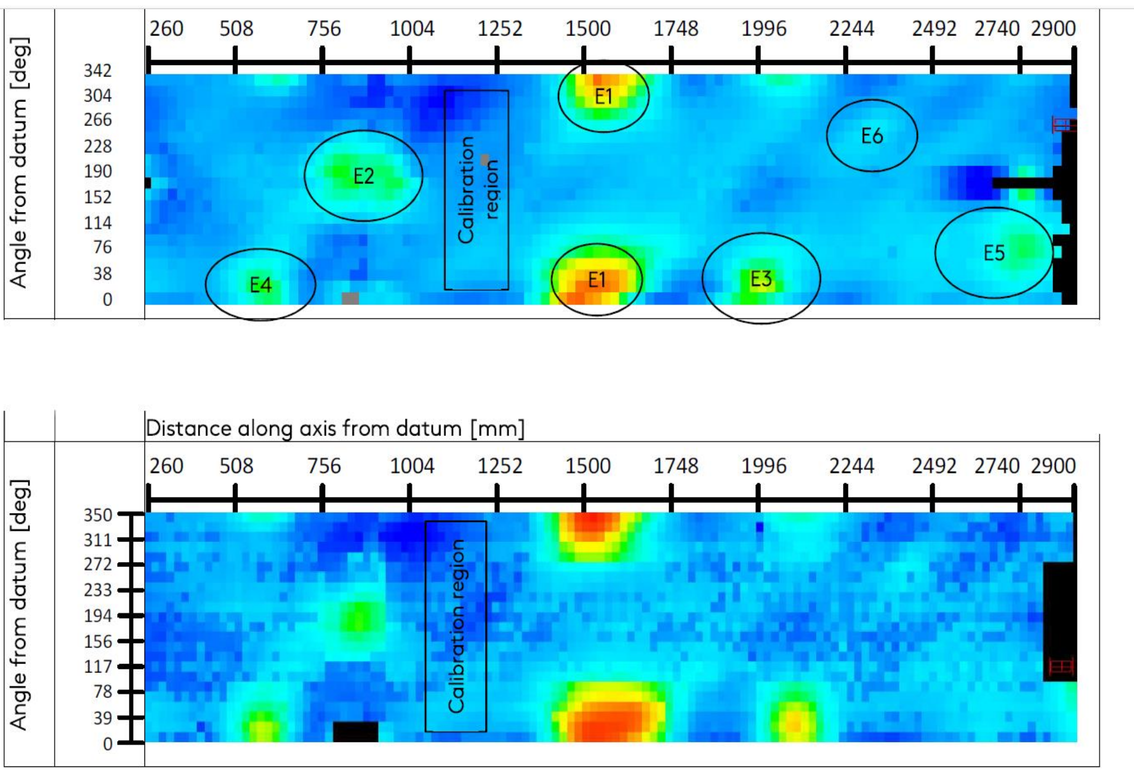


Figure A2-34: C-scans of a 10" sch 20 stainless steel clad pipe obtained using Eddyfi Lyft with a single-element probe (lower) and the PECA™ array probe (upper) (courtesy Eddyfi).

A2.7.4 HOIS trials

A HOIS CUI trial based on the original Shell PEC system was performed on straight, insulated 10" pipes which contained a significant number of corroded areas, covered by corrosion product (scabs) with a wide range of wall losses, from slight to almost through-wall. Hence these trials were successful in generating quantitative inspection performance information in terms of POD and false call rates.

For PEC applied through 100mm thick insulation and stainless-steel cladding, a step change in the hit/miss results was found at 50% wall loss, with all areas of corrosion with losses <50% missed and all those with >50% wall loss detected. The corroded areas on these 10" test pipes had an average circumferential/axial extent of about 150mm for a 50% wall loss.

Note that a limitation of all the NICE trials arose from the ex-service specimens available for the trials which were all straight pipes without any geometric features such as bends, tees or welded supports. Hence it was not possible to assess detection performance in the vicinity of these features, which are often known to be associated with CUI.

In the HOIS/OGTC trials (Burch and Collett, 2019), three different examples of PEC equipment (Eddyfi Lyft single sensors and PECA™ sensor array; Maxwell NDT PECT and TUV Rheinland Sonovation Sonopec) were trialled on a common set of manufactured 10” pipes with areas of wall loss introduced using advanced CNC machining methods to give morphologies representative of those found on examples of service induced external corrosion.

As the trials were performed on a common set of pipes, the relative performances of the different NDT methods trialled could be assessed. Of the three PEC methods, the Lyft trials (Eddyfi/Bilfinger) on the SS clad pipes gave the highest overall POD but not the lowest false call rate (2nd of 3). The lowest false call rate was obtained from the Sonopec trials (TUV Rheinland Sonovation) which gave the second highest overall POD.

The Eddyfi PECA™ array also gave significantly higher coverage rates than any of the single probe-based PEC scanning, but the array could only be applied to straight pipe sections not elbows. The highest POD obtained on the galvanised carbon steel clad pipes was achieved by the 50mm Eddyfi/Bilfinger Lyft trial, which was performed with the Eddyfi patent pending PEC-GS probe. Further details of the results obtained are given in the comprehensive HOIS/OGTC trial report (Burch and Collett, 2019 – available to HOIS members only).

A2.7.5 Summary

Method:	**Pulsed eddy current method for finding areas of metal loss caused by CUI**
Basis:	Local screening method with sensor footprint under the probe
Strengths:	• Relatively fast point measurements of relative wall thickness (conventional PEC) • Faster continuous scanning on some systems • Array probes can give significantly higher coverage rates • Single sided so can be applied to vessels and pipes
Limitations:	• Averages over sensor footprint area, which is larger than the thickness of the insulation, so can miss or severely undersize localised areas of CUI • Measurements are adversely affected by presence of ferromagnetic material in the insulation, including the outer casing. • Affected by local changes of geometry (e.g. tees), although can be applied to some elbows. • Slow to cover large areas (although array probes faster). • Mixed experiences of members: Some reported leaks immediately after conventional PEC inspection
Overall:	Although conventional PEC was developed principally for CUI inspection it is not widely used for this application currently due to its relatively low coverage rate and the averaging effect over the sensor footprint area, which can substantially reduce the apparent severity of the CUI and give limited POD for localised corrosion. Recent improvements in technology include single sensors and arrays which have potential for wider application due to increased scanning speed and greater sampling rate. These newer systems do however have a sensor footprint areas that are similar in size to those of more traditional PEC.

A2.8 Russell NDE Bracelet Probe

A2.8.1 Introduction

The Russell NDE Bracelet Probe is one of a number of “next generation” electromagnetic methods with potential for improved CUI inspection, compared with the pulsed eddy current approach detailed in Appendix A2.7. These newer electromagnetic methods permit continuous scanning which gives faster coverage than the stop-start inspection mode required for traditional PEC.

A2.8.2 Overview

The Russell NDE Bracelet Probe is a low-frequency electromagnetic method, which senses perturbations in the magnetic field pattern of the specimen due to changes in wall thickness.

The Bracelet Probe works on the principle of electromagnetics - effectively very low frequency eddy current, but the equipment does not measure the normal eddy current impedance parameters. Instead the amplitude of the magnetic flux induced by large coils in the material is measured. Full details of the method are not available due to commercial issues. The Bracelet probe technology for CUI applications is a near surface method so relatively unaffected by wall thickness.

The technology is more developed than the other advanced electromagnetic technologies covered in Appendix A3.6, and has been deployed for site applications for some years (TRL 9).

A2.8.3 Equipment details

This system includes 16 sensors mounted in an 8" (200mm) long bracelet (see Figure A2-35). This array can be used to scan pipe OD’s down to 6”, including the insulation, so that a 4" pipe with 50mm insulation can be scanned. Pipes up to 2m diameter have been examined. Typical scan speeds are up to 1.5 – 2 m per minute.

Figure A2-35: The Russell NDE bracelet probe, as applied to a pipe.

At present, wall thicknesses up to about 12 mm can be examined. Thicker pipes are difficult as they would require extremely low frequencies (a few Hz) and slow scanning. Insulation thicknesses up to 50mm can be inspected.

The quoted sensor footprint size for 50mm of insulation was c. 30mm diameter with the 3/4" coil diameter used. This is notably smaller than the corresponding footprint size for PEC which is greater than the insulation thickness. Hence the Russell NDE Bracelet Probe measurements should be less affected by sensor footprint averaging effects than PEC.

A2.8.4 Application to CUI inspection

For CUI inspection, as with most electromagnetic methods, the method can be adversely affected by outer metallic claddings on insulated pipes, depending on its material and also any metal within the insulation itself. The Russell NDE bracelet probe is applicable only to non-ferromagnetic cladding materials (e.g. stainless steel, aluminium as well as non-metallic claddings such as Ulvashield).

The presence of corrosion product did not adversely affect the performance of this equipment in the HOIS/OGTC trial.

An example of Russell NDE bracelet probe data from a 10" pipe with 50mm of insulation and stainless steel cladding containing CUI is given in Figure A2-36.

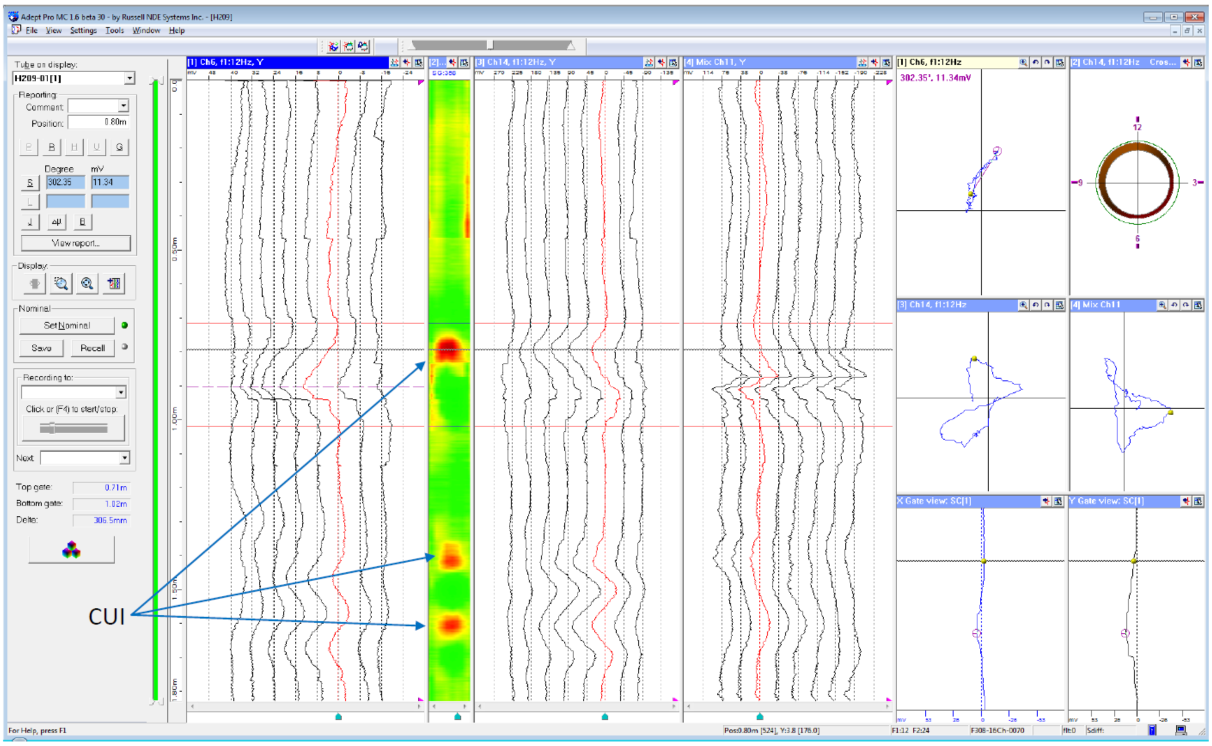


Figure A2-36: A screenshot of typical data from the Russell NDE Bracelet Probe.

A2.8.5 HOIS trials

In the first set of HOIS CUI trials (Burch and Kitchener, 2016), the Russell NDE Bracelet Probe was trialled at the NICE facility on straight, insulated 10" pipes which contained a significant number of corroded areas, covered by corrosion product (scabs) with a wide range of wall losses, from slight to almost through-wall. These trials were successful in generating quantitative inspection performance information in terms of POD and false call rates.

For the Russell NDE Bracelet probe applied through 50mm thick Rockwool insulation and stainless steel cladding, a step change in the hit/miss results was found at 25% wall loss, with all areas of corrosion with losses <25% missed and all those with >25% wall loss detected. The corroded areas on these 10" test pipes had an average circumferential/axial extent of about 70-80 mm for a 25% wall loss. This performance fully met the vendor’s expectations. Results on a calibration component with the same diameter and wall thickness as the test components showed that an area of 25% deep wall loss with a diameter of 25mm could just be detected in a known location.

Note that a limitation of all the NICE trials arose from the ex-service specimens available for the trials which were all straight pipes without any geometric features such as bends, tees or welded supports. Hence it was not possible to assess detection performance in the vicinity of these features, which are often known to be associated with CUI.

In the HOIS/OGTC trials (Burch and Collett, 2019), the Russell Bracelet probe was trialled on a set of manufactured 10” pipes with areas of wall loss introduced using advanced CNC machining methods to give morphologies representative of those found on examples of service induced external corrosion. Insulation thicknesses of 50mm and 100mm were both scanned.

The Russell NDE Bracelet probe trial gave the highest overall POD (although the POD for Eddyfi’s Lyft PEC equipment was only slightly lower) and lowest false call rates (by some margin) of all the systems trialled on the SS clad pipes. This system also gave the highest coverage rate, when averaged over both pipe wall thicknesses. The Bracelet probe was not however applicable to elbows nor galvanised carbon steel cladding. Note that for these cases, Russell NDE would use alternative methods (e.g. PEC). The 50mm insulation trial gave appreciably higher POD values than for the 100mm insulation trial, especially on the sch 80 pipes. Further details of the trial results are given in Burch and Collett (2019).

A2.8.6 Summary

Method:	**The Russell NDE Bracelet Probe is a low frequency electromagnetic method for finding areas of metal loss caused by CUI**
Basis:	Local screening method with sensor footprint under the probe
Strengths:	• Faster scanning than conventional PEC. • The sensor array gives greater coverage than the single probe PEC systems. • Single sided so can be applied to vessels and pipes • Quoted sensor footprint size is significantly smaller than PEC so may be more sensitive to localised areas of CUI. • Not affected by the presence of corrosion product in the HOIS trial. • A near surface method so relatively unaffected by wall thickness
Limitations:	• Not applicable to ferromagnetic cladding materials (e.g. galvanised steel). May also be affected by ferromagnetic material in the insulation (e.g. chicken wire). • Affected by local changes of geometry (e.g. bends, tees etc.) • Averages over sensor footprint, so may miss localised areas of CUI (although smaller effect than PEC if stated footprint size accurate) • Novel technology - limited information on field capabilities
Overall:	Potentially a faster and more sensitive method than PEC for CUI inspection on straight pipe sections under non-ferromagnetic cladding.

Appendix 3 Developmental NDT methods for CUI

CONTENTS

A3.1 Introduction

This Appendix covers developmental methods for CUI inspection and monitoring, with TRLs less than about 8. The stage of the development of the methods described in this Appendix varies, form those being research concepts with low TRLs (no higher than around 3-4) to others that are considerably more developed and have been the subject of both laboratory and field trials. With further development, some of methods have the potential to be used for routine in-service site inspections for CUI.

A3.2 Moisture Detection Imaging (MDI)

A3.2.1 Overview of method

Moisture Detection Imaging (MDI) is a recently developed technology from Acuren USA, for rapid identification of the presence of fluids within insulation without the use of any other NDT methods and without having to remove the cladding or insulation. Visual confirmation is provided in real time.

The equipment is based on low-energy X-rays which penetrate the cladding and are then Compton back-scattered by the material between the cladding and the pipe. Compton scattering is material-dependent, with the lower atomic number materials scattering more strongly than the higher numbered ones.

This technique detects organic compounds. Therefore, this device cannot distinguish between water, hydrocarbons, acids, bases, and organic liquids. However, the presence of any of these fluids in the insulation would warrant follow-up inspection.

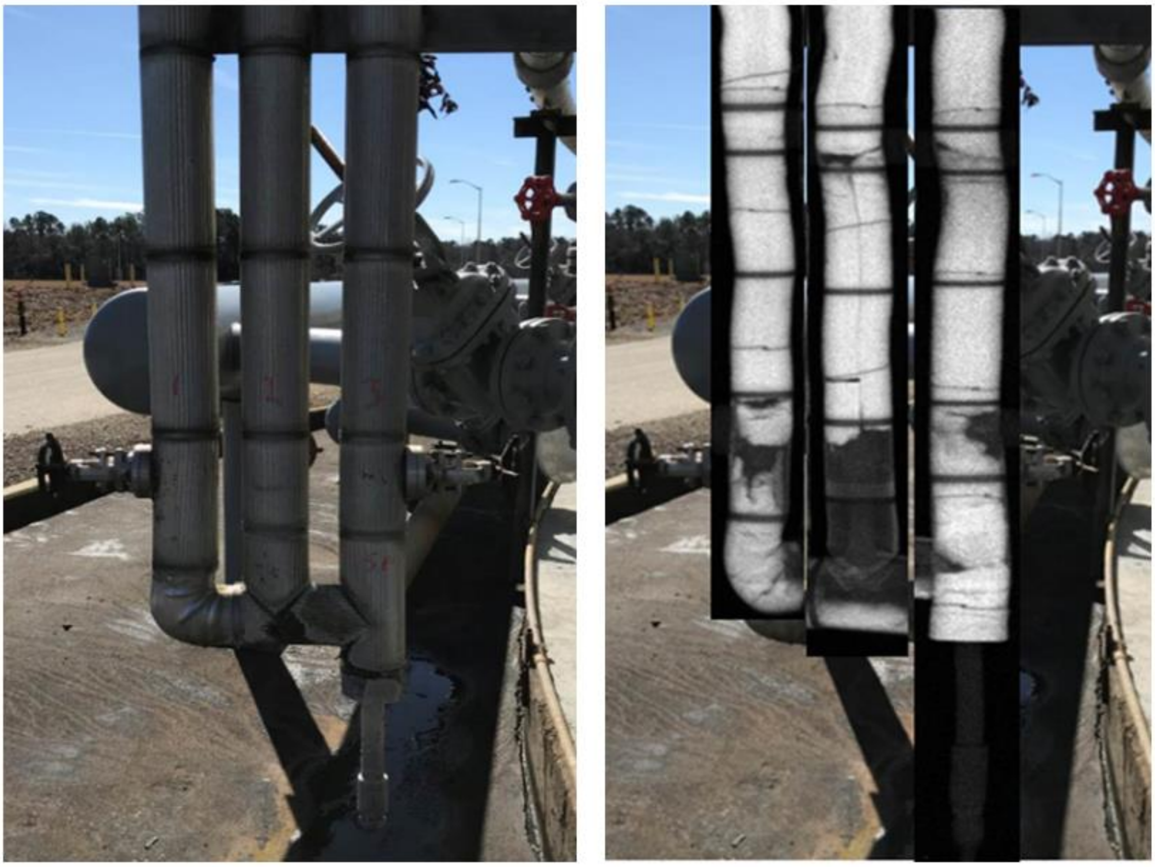
The use of low energy X-ray radiation presents some hazards that need to be managed in accordance with national and internal standards on radiological safety. Within the UK, the relevant legal requirements are given in IRR17, but other regulations apply elsewhere.

A photo showing MDI in use by a rope access technician is shown in Figure A3-1.

Figure A3-1 Acuren's MDI equipment for moisture identification (courtesy Acuren)

A3.2.2 Examples

An example of the output from MDI, is given in Figure A3-2. This shows on the left the insulated system and on the right with the corresponding MDI images overlaid. The lighter areas show the presence of wet insulation and the dark areas indicate where the insulation was missing. Prior to the examination, the insulation had been open to the elements at the top (10 meters) above grade to allow moisture ingress. The centre pipe section can just be discerned in the MDI images. Following this trial, all insulation was stripped to verify the results.



(a) Insulated system (b) MDI images showing wet insulation

Figure A3-2 Example of output from Acuren's MDI equipment showing moisture in insulation (courtesy Acuren). The image on the left shows the insulated system and on the right with the MDI images overlaid. See the text above for interpretation of the results.

A3.2.3 Application to CUI

Deployment of the MDI equipment is currently manual, and it is generally used to inspect at the 6 o'clock location on pipes and other insulated components for the presence of moisture between the cladding and the pipe surface. Assuming straightforward unimpeded access to the required locations, Acuren figures state that the following coverage rates can be achieved:

Straight Run	600m per 12-hour shift
Complex Piping	300m per shift
Complex Piping with rope access	200m per shift

It is said that MDI can form part of a CUI inspection programme by providing information that enables operators and owners to make decisions and prioritise where to focus more targeted inspection methods.

However as stated elsewhere, and as for all moisture detection methods, the presence of moisture in the insulation does not mean CUI is present and conversely dry insulation, at the time of inspection, may previously have been wet and contain CUI.

A3.2.4 HOIS trial results

The MDI equipment was not available at the time for the HOIS/OGTC CUI trial programme and hence its performance has not been independently assessed to date by HOIS.

A3.2.5 Summary

Method	**Moisture detection imaging (MDI)**
Basis:	Hand-held instrument to image the presence of organic liquids, including water, in insulation, based on X-ray backscatter.
Strengths:	• Detects the presence of water or hydrocarbon in the insulation under the cladding cladding • Easy-to-use method that can be used to rapidly scan insulated surfaces. • Low energy X-ray source • Only requires access to the surface
Limitations:	• Detects the presence of water or hydrocarbon in the insulation system, not corrosion • Minimum amount of moisture needed for detection unknown. • Needs to be placed in contact with, or close to, the insulated component under inspection • Radiation hazard – compliance needed with IRR17 if used in the UK
Overall:	Potential to form a part of a CUI asset integrity programme by providing information that enables duty holders to make decisions and prioritise where to focus more targeted inspection methods. Has already undergone field trials in USA.

A3.3 Guided Microwaves (RCNDE/BP)

A3.3.1 Introduction

The guided microwave method was developed as part of an RCNDE project in collaboration with BP, by Robin Jones and others at Imperial College. The following information was taken from a PhD thesis, kindly provided by Robin Jones (Jones, 2012).

This is a new inspection method which employs guided microwaves as the interrogating signal. Such guided microwaves provide a means of screening the length of a pipeline for wet insulation, by using the structure of a clad and insulated pipeline as a coaxial waveguide to support the propagation of electromagnetic waves. Areas of wet insulation will create impedance discontinuities in the waveguide, causing reflections of the incident microwave signal, allowing the water patches to be detected and located.

Hence this is an indirect method which does not detect CUI itself but only moisture in the insulation. In this respect, it is similar to the existing methods of passive thermography (Appendix A2.4.3), neutron backscatter (see Appendix A2.4.4) and MDI (Appendix A3.2). However, unlike the other two it has the potential to be permanently installed and therefore act as an early warning system at the first ingress of water into the insulation, preventing corrosion from initiating.

A3.3.2 Outline of method

The principle of the method is illustrated in Figure A3-3. A pipeline which has been fitted with thermal insulation and metallic cladding is effectively a scaled-up version of a coaxial cable, with the inner conductor formed by the pipeline, the outer conductor formed by the cladding, and the thermal insulation layer acting as the dielectric within the coaxial cable.

The insulated pipeline (comprising the pipe, insulation and metallic cladding) can be used as a coaxial waveguide to support the propagation of electromagnetic waves. The method involves exciting microwave propagation down the length of the pipeline with the use of an antenna-based excitation system inserted into the insulation, as shown in Figure A3-3. If the cladding has become damaged and allowed the ingress of water, then this patch of wet insulation will give rise to a reflection of the incident microwave signal. The reflected signal returns to the exciting antenna, where it is received, and used to detect the presence of water.

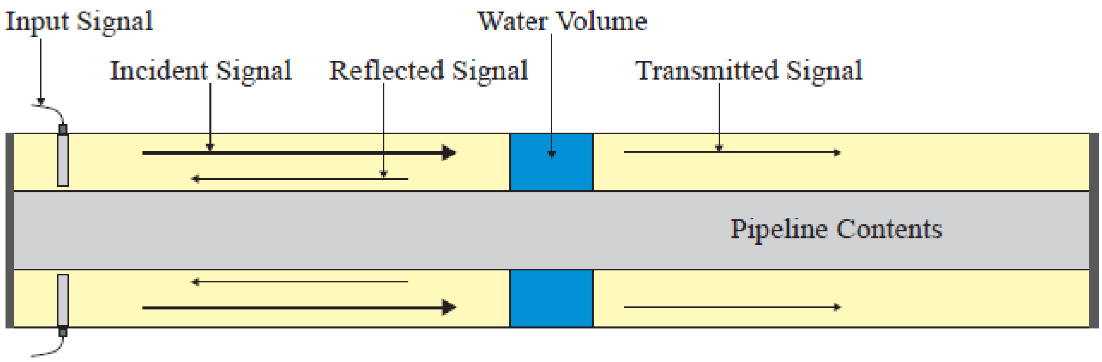
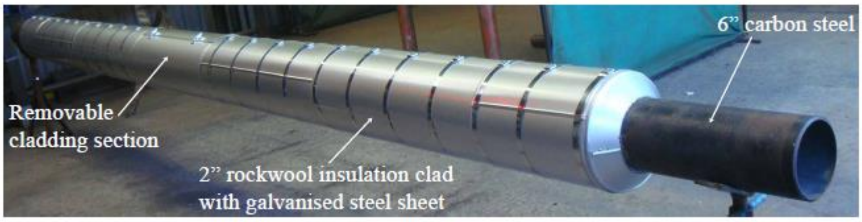
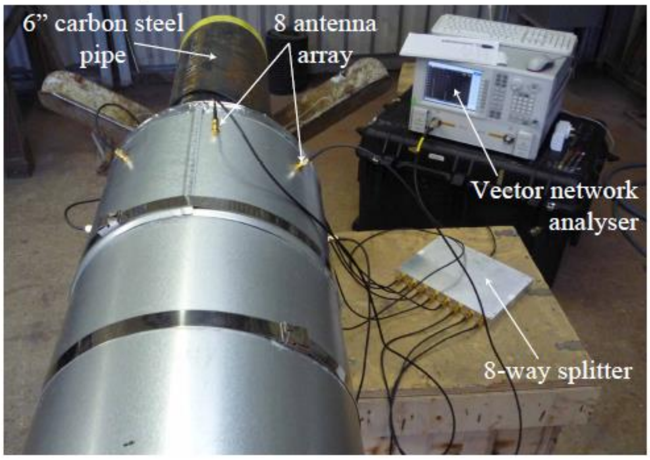


Figure A3-3 Principle of guided microwave method

The setup used for field tests is shown in Figure A3-4.



(a) Section of piping used for field test



(b) Experimental setup for field test

Figure A3-4 Experimental setup for field test

The results obtained for different amounts of wet insulation are shown in Figure A3-5. It can be seen that as little as 12.5% of the cross-sectional area containing water can be detected above the noise at a distance from the antenna of 2.7m.

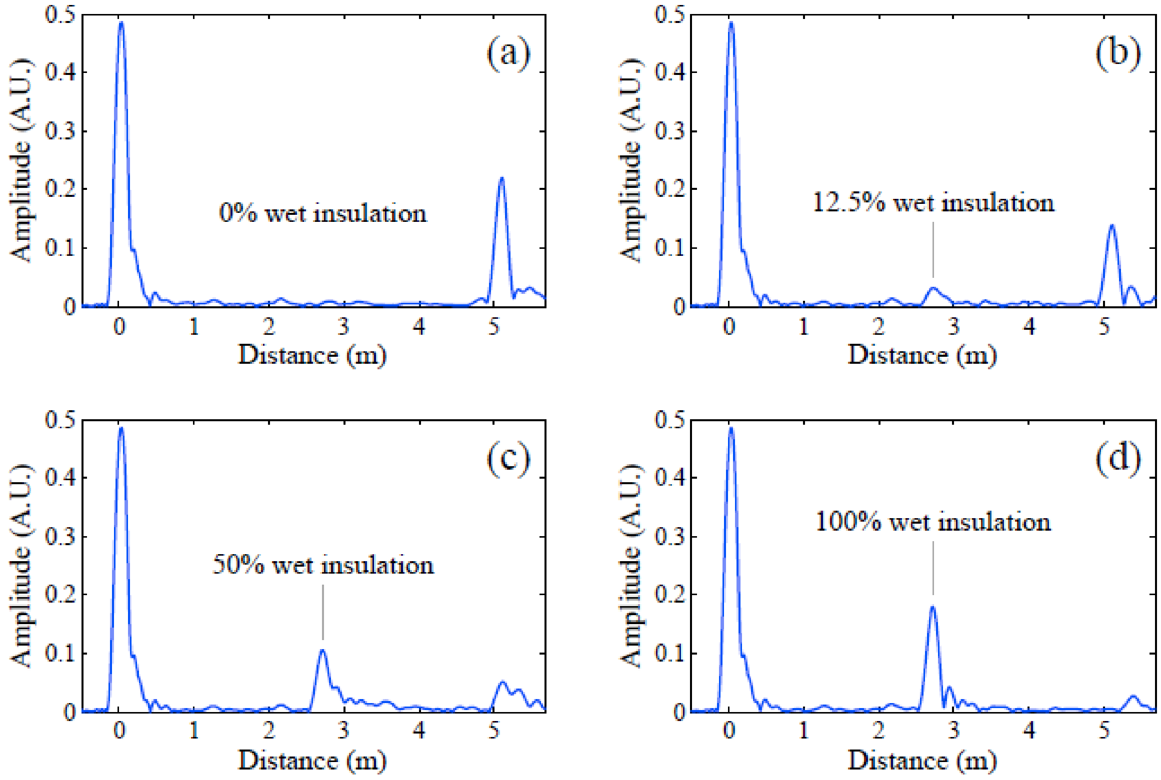


Figure A3-5 Four examples of signals from the field tests: (a) no wet insulation; (b) one section of wet insulation, equivalent to 12.5% cross-sectional extent; (c) four wet insulation sections, equivalent to 50% cross-sectional extent; and (d) all eight wet insulation sections, equivalent to 100% of the cross-section of the waveguide annulus occupied by wet insulation

There is a short dead-zone immediately in the vicinity of the antennas (~0.5m). Beyond this, the sensitivity is at its maximum, with gradual deterioration in sensitivity with distance due to material attenuation in the insulation and features such as supports. For polyurethane foam (no supports, therefore just material attenuation) tolerating a total attenuation of 30dB corresponds to a total inspection range of 50m (25m in either direction from antenna site). For Rockwool insulation tolerating a total attenuation of 30dB could correspond to a total inspection range of 100m (50m in either direction), though this is highly dependent on the frequency of pipe supports.

All of the experiments in the lab involved relatively short lengths of pipe (3 to 6m), due to spatial constraints in the lab where the work was performed. As the SNR achieved reached 40dB in the lab, tolerating a 30dB total attenuation in the signal is a reasonable metric.

These results indicate the method has good potential for detecting comparatively small sections of damp insulation within a few metres of the antenna system, but holes do need to be made in the cladding to insert the antennas into the insulated region. The figures given above indicate the method has potential for examination over substantial distances from the antenna system (25m to 50m). However, this had not been verified experimentally due to practical constraints on the sizes of the available test components.

The main finding was that it is possible to excite a guided microwave signal in a large coaxial waveguide with a high SNR. Experiments revealed that the method is highly sensitive to the presence of water in the waveguide. Measurements of the effect of different types of insulation demonstrated that dry Rockwool causes a very low attenuation of the microwave signal, while polyurethane foam insulation has a slightly higher attenuation coefficient.

An investigation into the effect of bends determined that, whilst significant mode conversion occurs at a bend, the transmission coefficient of the TEM mode is high for typical bend angles and bend radii in small diameter pipes.

The behaviour of the signal at a typical pipe support was also examined; the reflection from the support was minimal, whilst the transmission beyond the support remained relatively high.

A3.3.3 Potential strengths and weakness

Strengths

- Demonstrated detection of moisture in insulation within a few meters of the antenna array (down to c. 10% of the cross-sectional area of the insulation), with potential for detection over substantially longer distances, depending on the insulation material and other features such as pipe support frequency.

- Detection of water in insulation can provide an early warning of areas of a pipe at risk from CUI.

Weaknesses

- Does not detect corrosion directly, only damp insulation which may or may not be associated with CUI.

- Penetration of the cladding needed to insert the antennas, which may subsequently be vulnerable to water ingress

- Research method only – considerable development required for a field deployable system.

A3.3.4 Status

This method was developed for a now completed PhD thesis in 2012, and it is understood that no further work was then performed in this area.

Note that the equipment described in the following section (Appendix A3.4) appears to be based on very similar physical principles and is currently (2019) under active development and being evaluated in field trials.

A3.4 Guided Microwaves for CUI monitoring (ClampOn)

A3.4.1 Introduction

In early 2019, information was obtained from a Norwegian Seminar in Stavanger (NFV seminar on Strategic Inspection Management, Stavanger, Norway, February) regarding a system recently developed by Clampon, Norway. This was based on guided microwaves with a very similar principle to the RCNDE research project described in Appendix A3.3.

However the ClampOn (www.clampon.com) system is considerably more developed and was being trialled on-site to monitor for both moisture and corrosion product associated with CUI.

A3.4.2 Outline of method

The principle of this method is outlined in the Clampon slide shown in Figure A3-6. As with the RCNDE prototype, the method involves generation and detection of guided microwaves that propagate axially along the insulated pipe which acts as a coaxial cable, involving the metallic cladding as the outer shield and the pipe as the centre core.

An array of antennae is used to both generate the guided microwaves and then detect them.

The generated microwaves are reflected from both wet insulation and the corrosion products associated with CUI within the insulation.

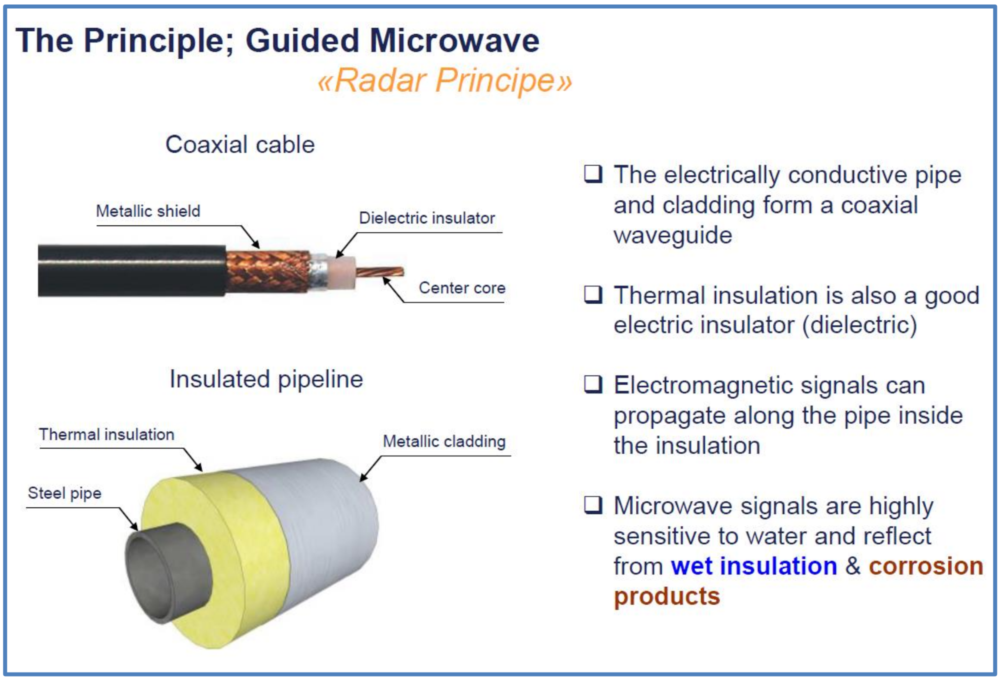


Figure A3-6 Principle of the Guided Microwave system from ClampOn (courtesy ClampOn)

The concept of the system is illustrated in Figure A3-7 which shows two installed CUI rings, and reflectors. The distances between CUI rings can be up to 100m, depending on the type of insulation.

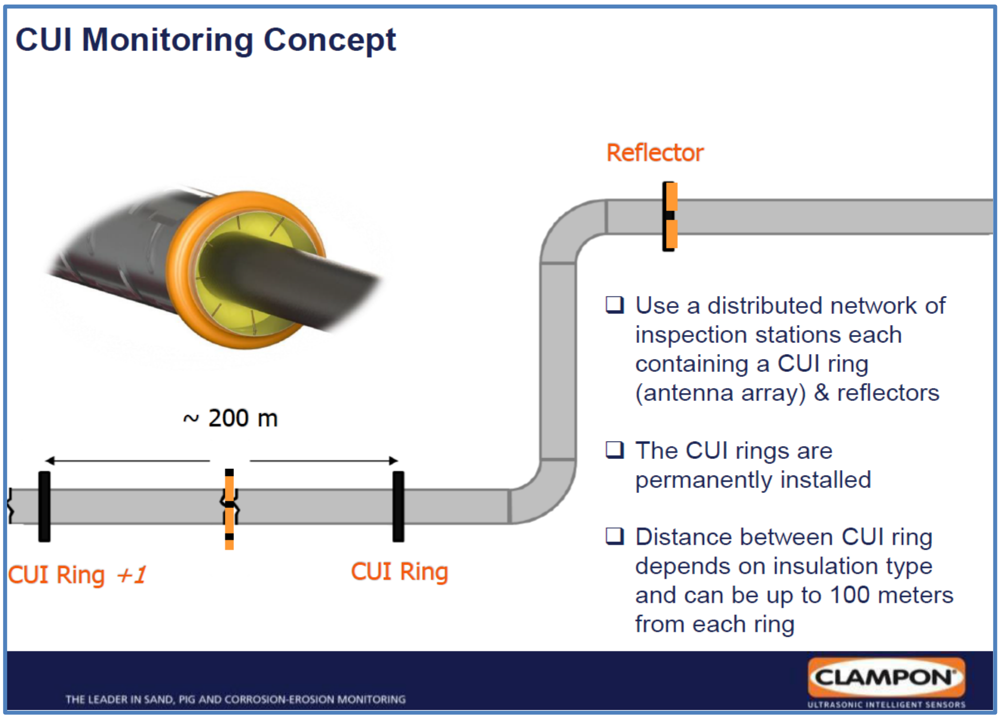


Figure A3-7 Concept of the Guided Microwave system from ClampOn (courtesy ClampOn)

Each antenna array emits guided microwaves, which pass through the insulating material without reflection. When there is water or corrosion residue in the insulation, the microwaves are reflected back towards the antenna array. Time of flight gives the distance from the antenna array to the area of water ingress or corrosion product. The signal amplitude provides information on the extent of the moist area or the severity of corrosion product.

The insulation can be mineral wool, polyurethane or other non-RF absorbing materials and the cladding must be metallic.

Importantly for continuous monitoring systems, the equipment is said to be intrinsically safe (IS) which allows it to be deployed in hazardous zones 0, 1 and 2.

A portable data logger can be used to periodically read out the data from the permanently installed antenna arrays.

A3.4.3 Potential strengths and weakness

Strengths

- Novel approach for CUI monitoring
- Use of IS sensors allows permanent monitoring in hazardous zones
- Long range – stated to be able to detect moisture and/or corrosion product up to 100m from antenna array

Weaknesses

- Moist insulation may not indicate presence of CUI
- Extensive moisture in insulation may limit range of method
- No independently validated information on effectiveness

A3.4.4 Status

This system is currently (2019) more developed than the RCNDE 2012 early prototype described in Appendix A3.3 and has been deployed for long term monitoring of part field trials on in-service equipment.

A3.5 Sniffer Dogs

A3.5.1 Introduction

Dogs are known to be extremely sensitive to smell and the use of specially trained sniffer dogs to detect the odour generated by special compounds (e.g. narcotic drugs, explosives) is well established. Dogs are for example widely used for security screening at airports and other sensitive locations such as ports, border crossings etc.

The use of dogs to potentially detect CUI is however novel and as yet unproven.

In March 2007, there was a presentation at a HOIS meeting regarding the use of “sniffer” dogs to detect CUI, by Rune Fjellanger of the Fjellanger Dog Training Academy in Norway. This was primarily at the invitation of Tor Harry Fauske, then of Statoil (now Equinor), who had been involved in the work. DNVGL were also involved. An update was provided at the June 2013 HOIS meeting.

Subsequently (November 2018) information was provided by Gassco on their more recent trials of this method.

A3.5.2 Outline of method

The concept of this method is that dogs might be able to “smell” the gases generated by active corrosion under insulation.

It is however important to note in this work that gas samples were taken from the potentially corroded insulated pipes, and then transported back to the Training Academy for the dogs to test in a controlled environment. It was not considered feasible to attempt to use the dogs to directly locate the CUI by smell on-site, due to distractions.

Figure A3-8 shows one of the dogs sniffing a gas sample placed on a numbered station on a rotating carousel. If the dog detects the target odour this is indicated by some clear change in the animal’s behaviour.

Figure A3-8 Dog sniffing a numbered gas sample.

Clearly dogs need to be trained for this specific application, and some dogs may be more effective than others at this process.

The presentation made in 2007 described an initial laboratory study (see Figure A3-9) which comprised a training phase for dogs on known samples, followed by a blind test. Encouraging results were reported from two particular dogs with 100% detection of high corrosion samples and about 50% detection of moderate corrosion, with 0-2% false calls.

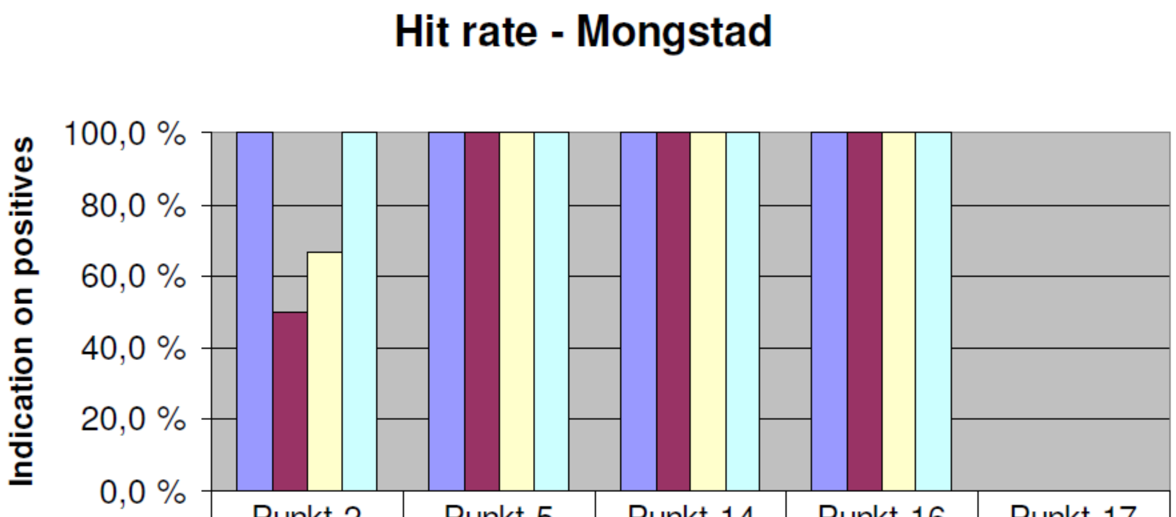
Figure A3-9 Setup for laboratory training phase.

A3.5.3 Initial results from trial on operating plant with CUI

The training phase was followed by a trial on an operating Statoil (now Equinor) plant (Figure A3-10), which involved sampling from insulated pipes, followed by removal of the insulation and visual inspection to determine the extent of any CUI present.

Figure A3-10 Gas sampling during phase 2 on an operating plant.

The results obtained in the plant trial are given in Figure A3-11 , which shows 100% detection on samples from four of the five sampled pipes having CUI, with a somewhat lower performance on the fifth pipe.



	Punkt 2	Punkt 5	Punkt 14	Punkt 16	Punkt 17
Tolman	100,0 %	100,0 %	100,0 %	100,0 %	0,0 %
My	50,0 %	100,0 %	100,0 %	100,0 %	0,0 %
Mac	66,7 %	100,0 %	100,0 %	100,0 %	0,0 %
Flick	100,0 %	100,0 %	100,0 %	100,0 %	0,0 %

Pipe #

Figure A3-11 Results reported from sniffer dog trials on gas samples from an operational plant.

The presentation at the June 2013 HOIS meeting included additional results from a double-blind site trial which are summarised in Figure A3-12. These showed promising results in that only 7% of corroded field locations were missed and 6% of uncorroded locations were incorrectly classified as suspect (false positives).

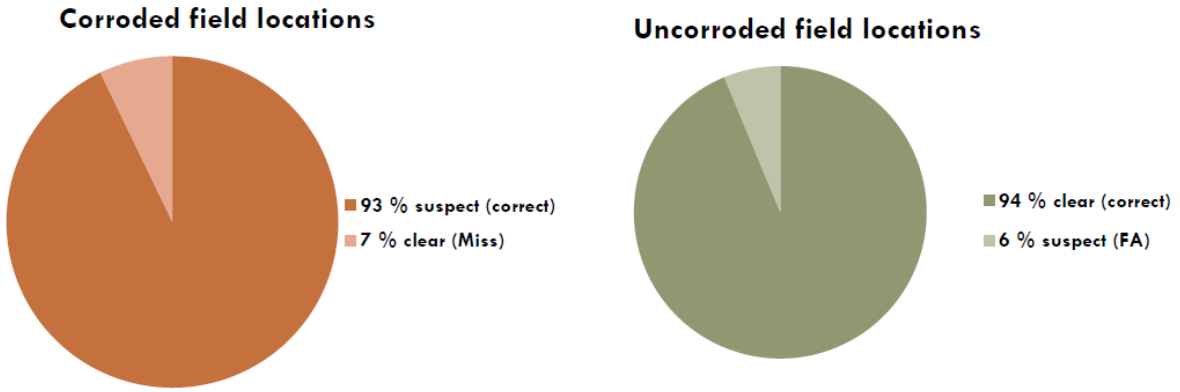


Figure A3-12 Further results reported from sniffer dog double blind site trial using gas samples from an oil and gas plant.

A3.5.4 Potential strengths and weakness

Strengths

- Novel approach for CUI inspection – something "different" with potential for CUI detection.

Weaknesses

- Penetration of the cladding needed to sample the gas, which may subsequently be vulnerable to water ingress.
- Results not immediate – gas samples have to be collected and taken to the dogs
- Effectiveness unproven
- Not yet used operationally despite trials dating back over 10 years.

A3.5.5 Status

An update on this approach was presented at a HOIS meeting in June 2013. This included reference to a proposed joint industry project to "ensure the readiness of FDTA CUI detection methodology for worldwide implementation", which was scheduled for a 2014 start and was planned to run for 2-3 years. No information was then available about the status of this JIP.

In 2013/14 this approach was considered by Total for a site trial as part of the first HOIS CUI trial programme. However, this did not go ahead for various reasons, including the need for a training phase prior to any CUI detection trial. This was considered to be necessary as the smell of gas samples with and without CUI at the Total site might have been different from those on Norwegian sites. This would confuse the dogs unless they had undertaken additional training on gas samples from the Total site. The need for a training phase would have been logistically challenging as it would have been necessary to first identify corroded and uncorroded areas without removal of the insulation, followed by collection of appropriate gas samples from the designated test points.

More recently, Gassco have been conducting further trials in Norway, and provided the following update for the November 2018 HOIS meeting:

- *"The overall results show that using dogs for locating corrosion is a viable solution. The specificity of the CUI dog system is high (93%), while the detection level is acceptable (80%). [Specificity is a measure indicating the precision with which making false calls is avoided, so in this case the false call rate was presumably 7%].*
- *Results illustrate that CUI dogs are similar to other NDT methods in that all methods have their strengths and limitations.*
- *CUI dog's technology can be used to detect corrosion and identify un-corroded areas in a cost-effective way.*
- *The Remote Scent Tracing (RST) technology is a promising method for detecting corrosion without stripping the insulation."*

A3.6 Advanced electromagnetic systems

A3.6.1 Introduction

In addition to the newer PEC systems (Appendix A2.7) and the Russell NDE Bracelet Probe (Appendix A2.8), there are a number of other systems that have been recently developed and/or are being developed based on advanced electromagnetic principles.

These include:

- Multi-frequency Eddy Currents (MFECT) (Exxam Systems)
- MWM (Jentek)
- LFET/OSET (TestEx)
- Eddy currents with GMR sensors (Robinson Research Institute)

Due to commercial confidentiality issues, there is limited information available about some of these systems.

A3.6.2 Multi-frequency Eddy Currents (MFECT) (Exxam Systems)

Introduction

The Multi-frequency Eddy Current (MFECT) method developed by Exxam Systems is currently (2019) based on a laboratory prototype rotary scanner with four bespoke planar electromagnetic sensor arrays, as illustrated in Figure A3-13. This method was described at the 2017 API Inspection Summit, which led to its evaluation as part of the HOIS/OGTC trials that started in 2018.

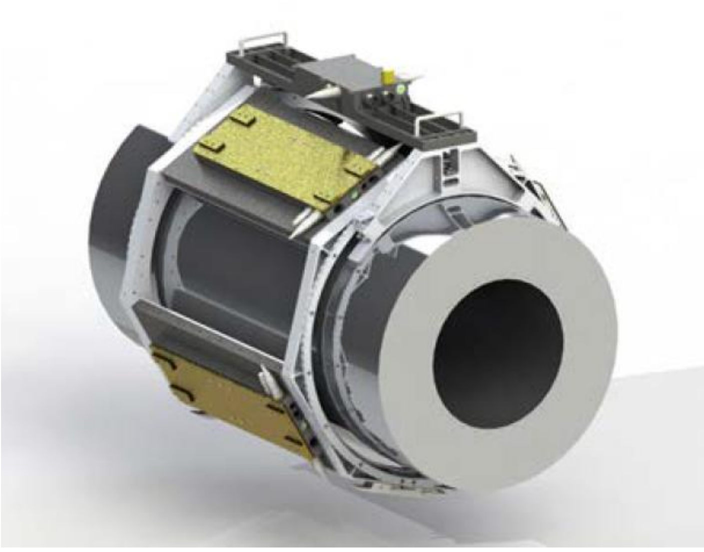


Figure A3-13 Schematic of Exxam systems MFECT circumferential scanner.

Technology Description

The planar array system is a multi-mode, multi-frequency tool, said to be capable of inspecting through up to 125mm (5") of insulation with metal jacketing in place. The MFECT tool is said to scan simultaneously for internal and external wall thinning and is said to be able to discern between internal and external corrosion.

Each planar array is comprised of a set of excitation drive coils and an array of magnetometers that make up the sensor bed for the array. The associated software was also developmental.

This laboratory prototype system used 4 planar detector arrays at a 90° spacing. These were scanned in a circumferential direction. Whilst a 90° rotation provided full circumferential coverage, in the trial the sensor assembly was rotated through 120° to give some overlap.

There were 96 sensors (magnetometers) per array. Multifrequency excitation was used while scanning. Multiplexing is used to obtain data at all frequencies during a single scan. A photograph of the device being used to scan a 10" pipe with 100mm insulation, as part of the HOIS/OGTC CUI trials, is given in Figure A3-14.

Figure A3-14 Exxam systems scanner on a 10” pipe with 100mm insulation, as part of the HOIS/OGTC CUI trials.

The unusual circumferential scanning mode covered an axial length of 250mm, and a 230mm axial increment between scans was used to provide some coverage overlap. To index the scanner axially between scans, it was physically moved the required the distance. Due to this design, there were fully circumferential coverage gaps at, and adjacent to, any obstructions such as the hanger supports and pipe supports.

More recently (February 2020), the tool has been fully automated for axial and circumferential travel (see Figure A3-15). The new automated tool covers 360° and is said to be able allow scanning of >120 m of pipe in an 8-hour work day. A flexible manual tool is also under development to reduce coverage gaps and to scan elbows.

Figure A3-15 Updated (2020) Exxam Systems automated scanner (courtesy Exxam Systems).

HOIS trial

Exxam Systems participated in the HOIS/OGTC CUI trials (Burch and Collett, 2019). All the areas of wall loss were external in these trials, so any capability of the MFECT tool to locate internal wall loss was not evaluated.

For the stainless steel 10" stainless steel clad pipes, it gave the 3rd of 5 overall POD of all methods and the joint highest false call rates. The results for 50mm insulation showed significant improvement compared with 100mm but did not meet the vendor’s prior expectation for volume sensitivity. The mean sizing differences showed under sizing between 10% and 30%WT, depending on insulation thickness and pipe schedule.

The trial results confirmed its lack of applicability to insulated pipes with galvanised steel cladding.

Summary

Method:	**Multi-frequency Eddy Current (MFECT) (Exxam Systems)**
Basis:	Low frequency, multi-frequency eddy currents.
Potential Strengths:	• Faster scanning and coverage rates than conventional PEC. • Reduced effective sensor footprint size compared with PEC • Eddy current method for near surface degradation only, so performance should be approximately independent of wall thickness • Single sided so can be applied to vessels and pipes • Said to be applicable to insulation thickness of 125mm but trial results only available for 50mm and 100mm insulation.
Potential limitations:	• Not applicable to ferromagnetic cladding materials (e.g. galvanised steel). Performance impacted by ferromagnetic material in the insulation (e.g. chicken wire). • Limited to straight pipes only. Not applicable to elbows and other geometric features. • Sensor array and scanner design gives fully circumferential lack of coverage at any obstructions (e.g. pipe/hanger supports). • Developmental
Overall:	Potentially a faster and more sensitive method than conventional PEC for CUI inspection on straight pipe sections without ferromagnetic cladding (e.g. galvanised steel) or chicken wire in the insulation

A3.6.3 MWM (Jentek)

Introduction
The Jentek electromagnetic technology is based on a Meandering Winding Magnetometer (MWM) array derived from technology developed at MIT in the 1980s. It is a technology that has been under development in the USA since at least 2006 with funding from a number of sources including PRCI and Chevron, for various applications including CUI inspection.

A scanner for CUI inspection using this technology is shown in Figure A3-16.

Figure A3-16 Jentek MWM technology for CUI scanning from their website (http://www.jenteksensors.com/).

Technology Description
The MWM-Array is an inductive sensor that operates like a transformer in a plane. The MWM-Array is based on the original MWM® (Meandering Winding Magnetometer) developed at MIT in the 1980s. A paper in Materials Evaluation (Denenberg et al, 2015) gives further details of this low frequency technology and its application to CUI inspection.

The JENTEK magnetometry methods have been adapted for the detection of internal and external corrosion through insulation and aluminium or stainless steel cladding. Segmented field magnetometry uses parallel rows of inductive and magneto-resistive (MR) sense elements at different distances from a linear drive to provide independent information used to estimate the properties of the weather jacket, insulation, and steel. The combination of the low frequency MR sense elements with the high frequency inductive sense elements allows the sensor to operate over a very wide range of frequencies. JENTEK's hyperlattices are used to correct for the presence of the weather jacket, the insulation thickness, the steel permeability, and the steel conductivity to measure the remaining pipeline wall thickness.

Capability to compensate for corrosion product if present is unknown.

Application to CUI

An apparently idealised example said to show flaws under insulation and cladding, from a Jentek document, is given in Figure A3-17.

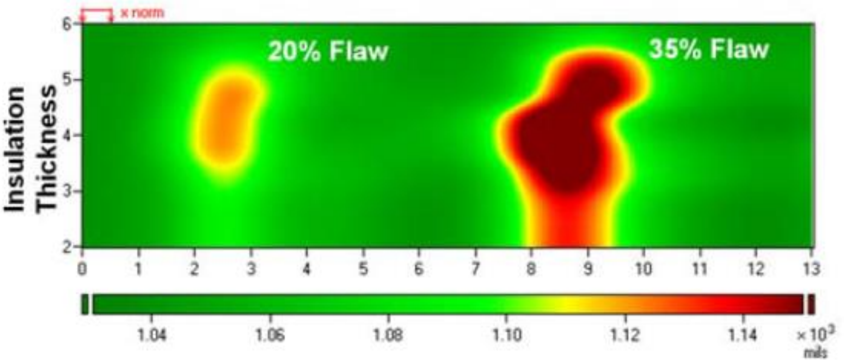


Figure A3-17 Jentek example said to show flaws under insulation and cladding .

Denenberg et al, 2015 give two tables, reproduced below, which summarise the claimed CUI inspection performance for the Jentek MWM array technology.

The detectability information given in Table A3.1 is reported to be from a blind performance evaluation trial on ex-service corrosion samples. The samples were 20" NB sch 10 pipes with 6.35 mm nominal wall thickness. These pipes were insulated with 50 mm of insulation and 0.51 mm thick aluminium cladding (weather jacket).

Also given in the table below is a column showing the volume (in ml) of the corroded area, assuming the area is flat-bottomed. The values below show how the minimum detectable volumes increase with the wall loss and the diameter of the corroded area.

Table A3.1: Jentek MWM CUI detectability from Denenberg et al, 2015

Corrosion area diameter (mm)	Minimum detectable wall loss (% wall thickness)	Volume of wall loss (ml)
25	65	2.0
51	50	6.5
76	30	8.6

Table A3.1 states that a corrosion area with a diameter of 76mm can be detected with 30% wall loss. This is similar to the performance achieved by the Russell NDE Bracelet probe in an initial HOIS trial (Appendix A2.8) on very similar ex-service test specimens (10" sch 20 pipes, with 6.35mm nominal wall thickness, 50mm of insulation and stainless steel cladding). In the

HOIS trial all areas of wall loss greater than 25% were detected and their average extent was c. 70-80mm. However, the Russell NDE Bracelet probe may have been capable of detecting 25% deep areas of wall loss with smaller diameters than those in the test components, given its stated sensor footprint size of only 30mm.

No quantitative information is available on the sensor footprint size of the MWM array, nor its scan speed, which is however stated as being comparable with phased array UT.

Table A3.2 summarises the Jentek MWM CUI capability. It should be noted that the maximum wall thickness for MWM is very similar to that specified for the Russell NDE Bracelet Probe.

Table A3.2: Jentek MWM CUI capability from Denenberg et al, 2015

Cladding	Insulation thickness	Pipe
Aluminium or stainless steel up to 1 mm thick	All materials up to 76.2 mm thick	Carbon steel up to 12.7 mm thick; no temperature restriction (verified up to c. 600 °C)

HOIS trial
Jentek were approached regarding a blind HOIS trial prior to the initial series of trials that started in 2014 but declined to participate. Hence it is not possible to verify the accuracy of performance information given above.

Summary

Method:	**The Jentek MWM technology is a low frequency electromagnetic method based on a sensor array for finding areas of metal loss caused by CUI**
Basis:	Local screening method with sensor footprint under the probe
Potential Strengths:	• Faster scanning than conventional PEC. • The sensor array gives greater coverage than single probe PEC systems. • Single sided so can be applied to vessels and pipes
Potential limitations:	• Up to 75mm of insulation. • Wall thickness up to 12mm. • Not applicable to ferromagnetic cladding materials (e.g. galvanised steel). May also be affected by ferromagnetic material in the insulation (e.g. chicken wire). • Likely to be affected by local changes of geometry (e.g. bends, tees etc.) • Averages over sensor footprint (no information available on its size), so may miss localised areas of CUI. • Novel technology - limited information on field capabilities.
Overall:	Potentially a faster and more sensitive method than conventional PEC for CUI inspection on straight pipe sections under no more than 75mm of insulation and non-ferromagnetic cladding. Limited to thinner walled pipes (up to 12mm).

A3.6.4 LFET/OSET(Test Ex)

Introduction
TextEx (USA http://testex-ndt.com/) are currently offering advanced electromagnetic sensor systems for CUI inspection.

Their initial sensors were based on low frequency eddy currents (LFET) but these have been supplemented by the Off Surface Electromagnetic Method (OSET). The principle of LFET is shown in Figure A3-18.

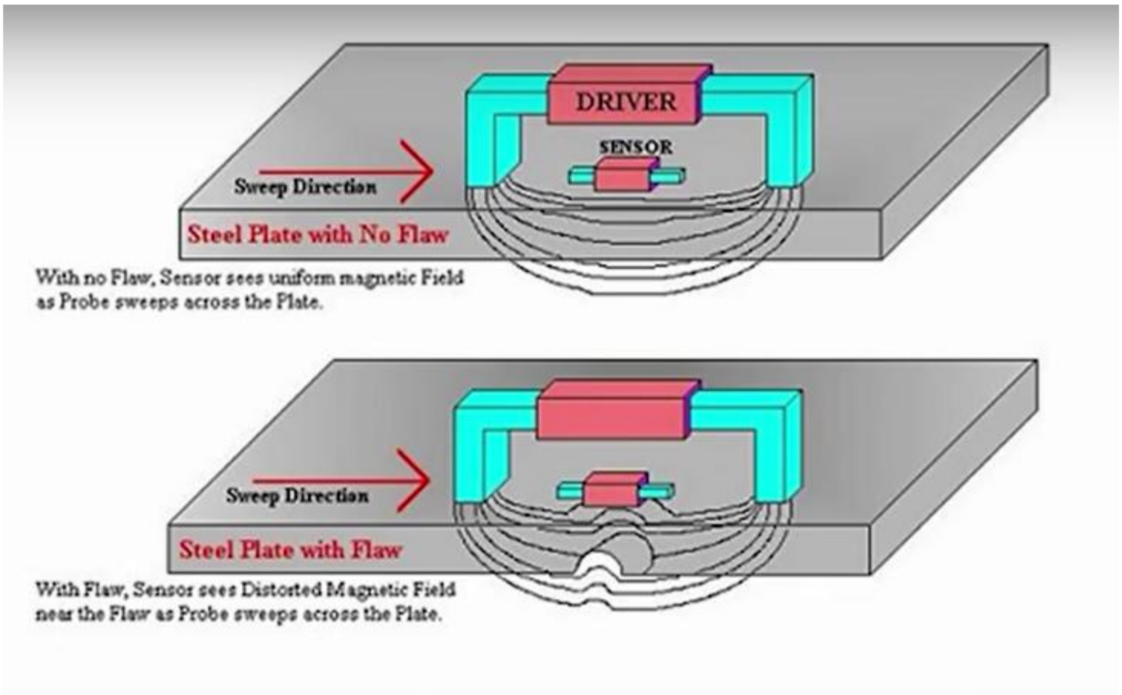


Figure A3-18 TestEx schematic of principle of LFET.

Technology description

A photo of the OSET Scout system, taken from the TestEx website, is shown in Figure A3-19.

Figure A3-19 TestEx OSET Scout scanner for CUI inspection (courtesy TestEx)

Figure A3-20, taken from a TestEx online video, shows deployment of the scanner on-site.

Figure A3-20 TestEx OSET Scout scanner deployed on-site (courtesy TestEx)

Relevant features of this equipment, as stated by TestEx, include:

- Portable electronics
- Light-weight scanner design that fits most piping, vessels, and tanks starting at 2″ (50.8 mm) diameter piping and ranging up to flat surfaces

- Type of insulation (calcium silicate, mineral wool, fiberglass, etc.) has no effect on signal response. The presence of moisture within the insulation also has no effect
- Detects surface corrosion (wall loss, pitting) on piping of any wall thickness and large area I.D. corrosion on schedule 40 piping
- Can locate butt welds
- Encoded data with mapping option
- Circumferential scanning technique on cladding overlaps to avoid “reduced sensitivity/dead zones”
- Positioning device displaying circumferential position and reference angle to assure straight scans and angular position of the next scan

The TestEx current CUI capabilities are said to be as follows:

- For pitting corrosion, scanning through stainless steel jacketing with up to 3" (75 mm) of insulation, aluminium jacketing with up to 2" (50mm) of insulation.
- Pits with 30% wall loss and 1″ (25.4mm) diameter are said to be detectable.
- Scanning through any type of insulation: calcium silicate, mineral wool, fiberglass, etc.
- Locating butt welds
- Detection of surface corrosion (wall loss, pitting)
- Detection of larger zones of ID corrosion

HOIS trial
TestEx were approached more than once regarding participating in the initial blind HOIS trials but declined to participate

Summary

Method:	**The TestEx OSET technology is a low frequency electromagnetic method based on a sensor for finding areas of metal loss caused by CUI**
Basis:	Local screening method with sensor footprint under the probe
Potential Strengths:	• Faster scanning than conventional PEC. • Single sided so can be applied to vessels and pipes • Some capability for ID and OD inspection on thinner walled pipes. • Some evidence of successful field applications in the USA.
Potential limitations:	• Up to 75mm of insulation, depending on the cladding material • Not applicable to ferromagnetic cladding materials (e.g. galvanised steel). May also be affected by ferromagnetic material in the insulation (e.g. chicken wire). • Likely to be affected by local changes of geometry (e.g. bends, tees etc.) • Averages over sensor footprint (no information available on its size), so may miss localised areas of CUI. • Novel technology - limited information on field capabilities.
Overall:	Potentially a faster and more sensitive method than conventional PEC for CUI inspection on straight pipe sections under no more than 75mm of insulation and non-ferromagnetic cladding.

A3.6.5 Giant Magnetoresistance (GMR) Sensors (Robinson Research Institute, NZ)

Introduction

This method is again based on low frequency eddy currents, but with a novel excitation approach and sensitive sensors based on the principle of giant magnetoresistance sensors. This developmental equipment is from the Robinson Research Institute in New Zealand.

The equipment comprises a custom scanner assembly containing a fully circumferential excitation coil and an array of sensors. GMR sensors have been used before to detect CUI, but the pipe encircling coil is a new approach (see Figure A3-21).

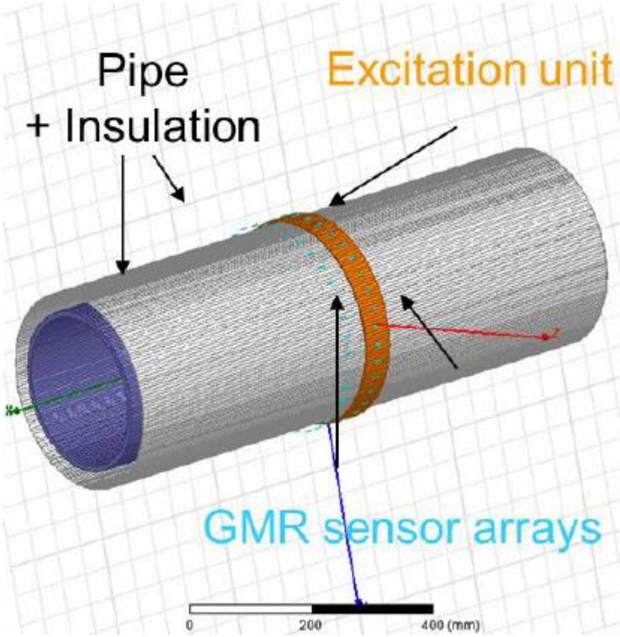


Figure A3-21 Principle of eddy current method with GMR sensors used by Robinson Research Institute.

Technology Description

The technology involves a developmental proprietary eddy current method with an insulation encircling high current, low multi-frequency excitation source and a high density magnetic (GMR) sensor array.

This equipment induces eddy currents in a pipe by means of a copper ring around the insulated, clad pipe. High currents (up to 300A) in this ring are setup using a 12v lead acid battery similar in size to a car battery. The eddy currents flow all the way around the circumference of the pipe. These are sensed by an array of Giant Magnetoresistance (GMR) sensors around the pipe. These sensors were used because of their high sensitivity and low noise at low frequencies.

There are 96 sensors in all, which were paired, so there were 48 circumferential positions. The sensor ring was split into 4 quadrants, with gaps between each quadrant. Because of this the ring needs to be rotated by 45° and the scans repeated to obtain full circumferential coverage.

Three frequencies are used. Separate axial scans were needed for each frequency, as multiplexing capabilities are not yet available. Hence a total of 6 axial scans are needed to scan the full circumference of a pipe, including the ones at 45° offset required to achieve full circumferential coverage.

The scanner is currently (2019) a prototype/proof of concept system (see Figure A3-22). An industrial partner would be needed to develop a commercial system.

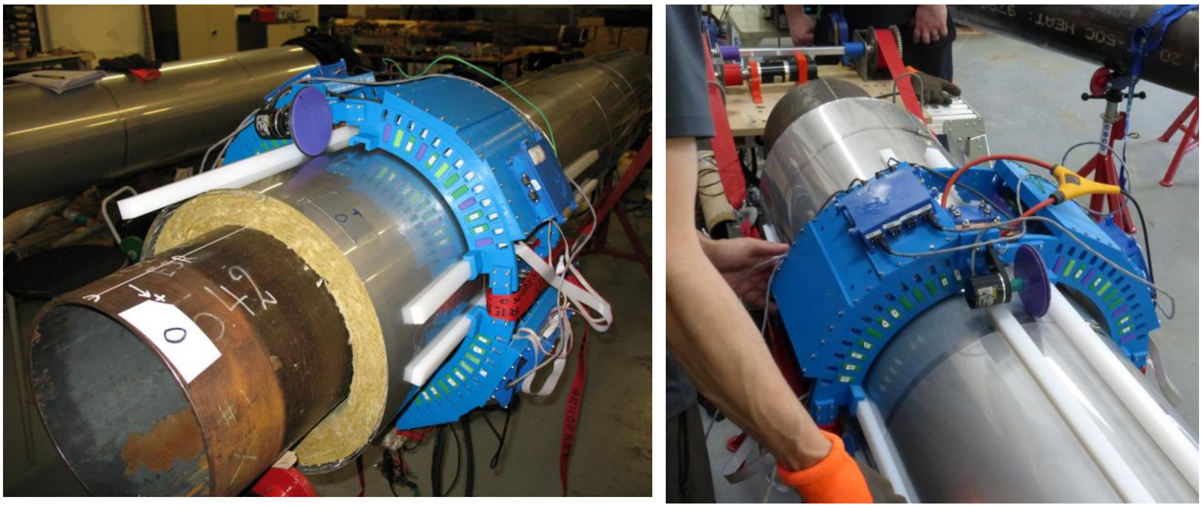


Figure A3-22 Robinson Research Institute GMR scanner on a 10" pipe with 50mm insulation.

Due to the design of the scanner, hanger and pipe support obstructions produce fully circumferential gaps in coverage at the obstructions and adjacent to it.

HOIS trial

Despite the considerable distance required for travel, this system was included in the recent HOIS/OGTC trials (Burch and Collett, 2019). It was only trialled with 50mm thick insulation as it was not considered applicable to the 100mm insulation.

The scanner was intended for straight pipe sections only and hence the elbows and the regions around the supports were not scanned. The POD achieved improved with pipe wall thickness. The presence of chicken wire in the insulation significantly impacted on detection performance. Quantitative sizing values were not reported. The severity ratings used showed no significant correlation with the benchmark values for maximum wall loss. Its achieved volume sensitivity was similar to the vendor’s prior expectation.

The trial confirmed the technology was not applicable to galvanised cladding.

Summary

Method:	**The Robinson Research Institute GMR-based technology is a low frequency electromagnetic method based on a sensor array for finding areas of metal loss caused by CUI**
Basis:	Local screening method with sensor footprint under the probe
Potential Strengths:	• Faster scanning than conventional PEC. • The sensor array gives greater coverage than single probe PEC systems. • Single sided so can be applied to vessels and pipes • HOIS/OGTC trials showed sensitivity to CUI volume loss was ~ 5 ml (50% POD) for stainless steel clad pipes with 50mm insulation, which met the vendor's prior expectation.
Potential limitations:	• There has been no testing of the system for an insulation thickness >50mm. • Not applicable to ferromagnetic cladding materials (e.g. galvanised steel). Also, performance impacted by ferromagnetic material in the insulation (e.g. chicken wire). • Not applicable to local changes of geometry (e.g. bends, tees etc.) • Supports and obstructions give fully circumferential lack of coverage for all axial locations within ~150mm of the obstruction.
Overall:	A novel developmental approach for advanced EM inspection of CUI. Further development would be needed for a commercial, field applicable system.

A3.7 Electrical Impedance Spectroscopy (Inspection Technologies)

A3.7.1 Introduction

Inspection Technologies (www.inspectiontechnologies.co.uk) have developed a prototype system for CUI monitoring based on the principle of Electrical Impedance Spectroscopy.

Information on this approach was presented at the British Institute of NDT's annual conference in 2017 (Diamond et al, 2017).

A3.7.2 Outline of method

The method is based on electrical impedance spectroscopy (EIS) which uses circular electrodes attached to the pipe being monitored and separated by a distance of a few meters. The resistance between these electrodes is measured. The development of CUI is expected to reduce the wall thickness and hence increase the resistance between the electrodes.

The measurements at different frequencies provide information for different depths within the pipes since, due to the skin effect, the highest frequencies sample only the nearest surface layers of the pipe. Lower frequencies give more information on any changes extending to larger depths below the surface.

The concept for monitoring extensive lengths of pipework involves large numbers of miniature EIS units wlth each one forming a node in a distributed network of in-situ corrosion sensors.

In principle, to avoid any removal of cladding and insulation, the sensors can be attached to exposed metalwork outside of the insulation such as valves, flanges etc.

A3.7.3 Status

There has been a field trial in Norway of this technology, which indicated increasing resistance associated with ongoing surface corrosion along the full length of the pipe between pairs of sensors.

An Oil and Gas Technology Centre (OCTC) funded trial is underway to assess the sensitivity of the method for monitoring the progression of more localised CUI at a single point between sensor pairs separated by a few metres.

The sensors are not currently intrinsically safe (IS) and so cannot be deployed in hazardous environments without a hot work permit which is a significant issue for monitoring technology.

A3.8 Other developmental methods for CUI monitoring/ detection

The latest information from the OGTC indicates the following developmental technologies are considered to have potential for CUI detection or monitoring

A3.8.1 Corrosion Radar (monitoring)

CorrosionRADAR (https://www.corrosionradar.com/) is a UK company based in Cranfield. They have been developing technology for monitoring the development of CUI, and the presence of moisture in the insulation. The approach is based on a set of sensors that need to be permanently installed onto the pipe surface, under the insulation. Hence this technology either involves removal of insulation for an existing plant or installation from new for a site yet to be commissioned.

CorrosionRADAR is a novel distributed sensing technology for detecting and predicting corrosion under insulation. Comprised of a long thin flexible, permanently mounted sensor, it is said to be able to detect and locate corrosion and moisture in inaccessible locations.

Figure A3-23 shows the concept of the sensors installed under the insulation of a pressure vessel.

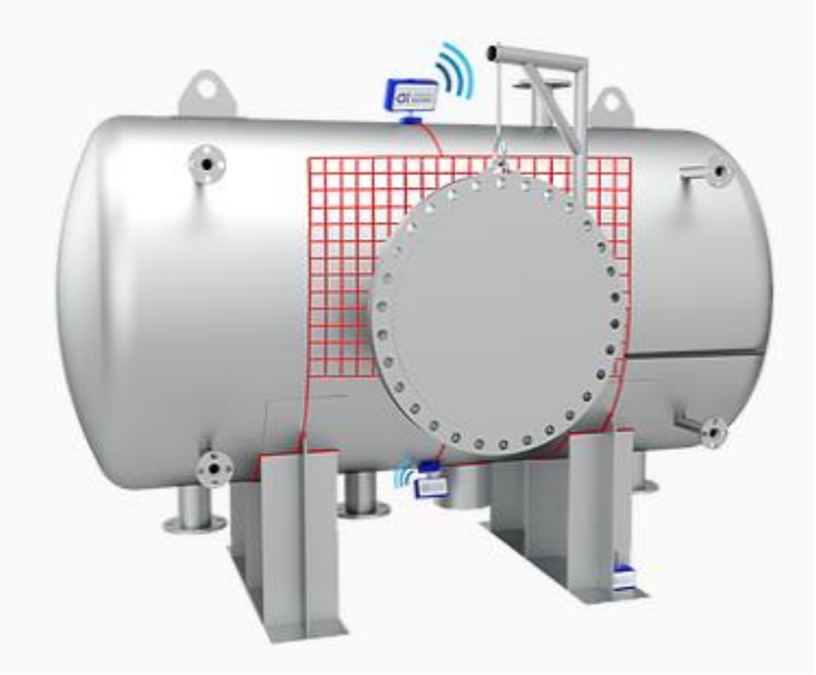


Figure A3-23 Concept of CorrosionRADAR sensors installed under the insulation of a pressure vessel to monitor for CUI and moisture in the insulation.

The method is understood to be based on measurements of changes in the physical properties of the sensor wires themselves, not the component on which it is installed.

It is unclear how it can be ensured that the condition of the sensors can be taken as being representative of the surface of the component on which they are installed. For example, in real life, the component will be coated and corrosion will only occur once there has been local failure to the coating. If uncoated the sensors are likely to have started to corrode well before the component on which they are installed. If coated, the condition of the sensor coating will not necessarily be the same as that of the component.

It is said that the sensor sensitivity can be adapted to suit the environment and risk-level of the asset, providing corrosion management control. The multiple configurations of corrosion and moisture sensors are most effective at monitoring piping systems. This method can also be used to encircle pipes, vessels and vats for circumference corrosion detection. A mesh configuration can be used for the highest value vessels and pipework and a helical configuration is also available.

Further details of this technology including the principles behind the sensors, their performance and its effectiveness for CUI monitoring are currently unknown.

A3.8.2 SubTeraNDT (inspection)

Sub TeraNDT are a UK company based in Cornwall (http://subterandt.com/). They have developed a terahertz based imaging system which can be deployed by means of a handheld scanner.

Terahertz radiation consists of electromagnetic waves within the ITU-designated band of frequencies from 0.1 to 30 terahertz (THz). One terahertz is 10^{12} Hz or 1000 GHz. Wavelengths of radiation in the terahertz band correspondingly range from 1 mm to 0.1 mm (or 100 μm). Because terahertz radiation begins at a wavelength of one millimetre and proceeds into shorter wavelengths, it is sometimes known as the submillimetre band.

Terahertz radiation can penetrate thin layers of non-conducting materials but is blocked by thicker objects and anything metallic.

Terahertz radiation occupies a middle ground between microwaves and infrared light waves known as the “terahertz gap”, where technology for its generation and manipulation is in its infancy. It represents the region in the electromagnetic spectrum where the frequency of electromagnetic radiation becomes too high to be measured digitally via electronic counters, so must be measured by proxy using the properties of wavelength and energy. Similarly, the generation and modulation of coherent electromagnetic signals in this frequency range ceases to be possible by the conventional electronic devices used to generate radio waves and microwaves, requiring the development of new devices and methods.

Potentially therefore Terahertz imaging may have potential for detection of moisture in insulation or the corrosion product associated with CUI for insulation systems without metallic cladding, such as the newer materials such as Ulvashield.

Terahertz imaging sensors have been developed for security applications but their application to CUI detection is at an early stage of development.

A3.9 Gas sampling methods (Shell)

A3.9.1 Outline of Method

In their 2012 HOIS questionnaire response, Shell Global Solutions International provided the following information regarding a novel gas sampling method for CUI detection:

"Screening method for newly insulated/coated piping based on the reaction of acetic acid with ferro-oxides - patent application filed. The space underneath cladding could be flushed with a gas containing trace amounts of acetic acid and an inert compound X (assuming ratios of 1:1).

The off-gas could be measured and the concentrations compared. When the concentration of acetic acid is lower than that of X, acetic acid has been annihilated; this would indicate the presence of corrosion products and it could allow a quantitative determination of the corroded area.

Longer lengths of insulated piping could be inspected by just a small entrance and exit hole, where tubes should be connected. Further testing is pending internal budget approvals".

A3.9.2 Potential benefits

"No need for large scale scaffolding - cherry picker may be enough; pumping gases around is simple and low cost; sensitivity is believed to be high, yet pending further study (uptake by insulation materials, for instance)".

A3.9.3 Further developments

"Study the implications of the presence of insulation material on the contact between the steel surface (where the corrosion products are) and the acetic acid component in the sweeping gas; determine sensitivity (how small an amount of corrosion product can be reliably detected?)".

Development costs

Estimated at between 100,000 and 300,000 Euro.

A3.10 Capacitive imaging for NDE

A3.10.1 Introduction

Capacitive imaging for NDE is a research project undertaken by the Universities of Warwick and Strathclyde, as part of the Research Centre for NDE (RCNDE), with some potential for CUI inspection.

A3.10.2 Outline of method

The general approach of this method is to use a co-planar capacitive electrode to detect changes in the local electrical characteristics within a sample. A schematic diagram of the capacitive imaging approach is shown in Figure A3-24. The co-planar probe, which contains two or more metal electrodes, generates an electric field distribution within the test material when an AC voltage is applied between the positive and negative electrodes. The presence of the sample under test will affect the resultant electric field pattern.

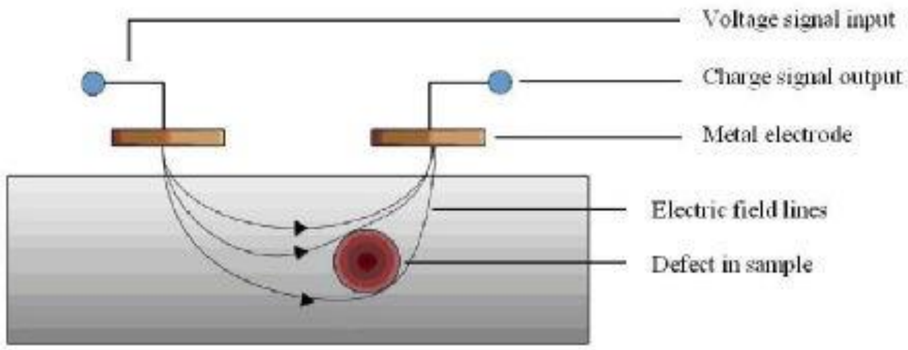


Figure A3-24 Schematic of University of Warwick capacitive imaging method for NDE.

A3.10.3 Equipment

Experimental equipment has been developed for this method. Typical capacitive imaging probes are shown in Figure A3-25, fabricated by etching a printed circuit board (PCB) substrate.

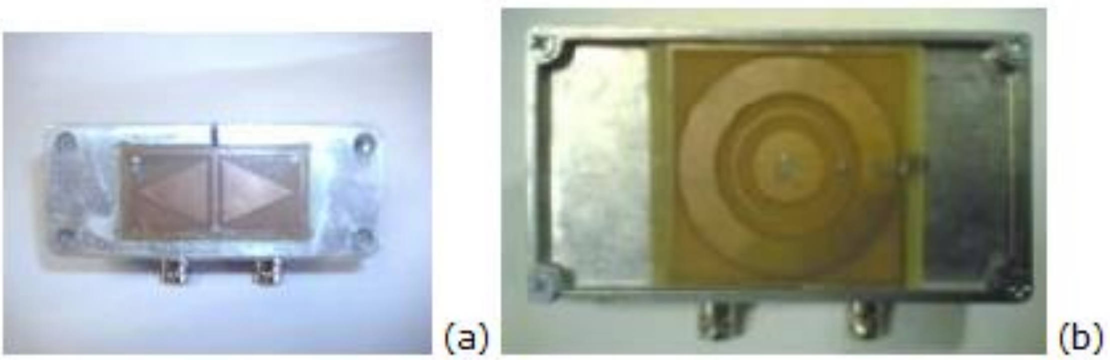


Figure A3-25 a) Photograph of a pair of triangular electrodes, mounted in a shielded metallic container. The triangular electrodes in this example were each 20 mm wide in the horizontal direction. (b) A concentric electrode design.

The probe was part of an instrumentation system that could be used for imaging, and a schematic diagram of the basic instrumentation is shown in Figure A3-26. To measure the signal at any particular location, a single frequency AC signal was applied as the driving voltage to one of the electrodes. The frequency of operation could be adjusted from 10kHz to 1MHz, noting that all the images below were obtained at a frequency of 1MHz. An increased sensitivity was obtained by using a lock-in amplifier, which converts the AC voltage signal into a DC voltage proportional to the amplitude of the received AC signal.

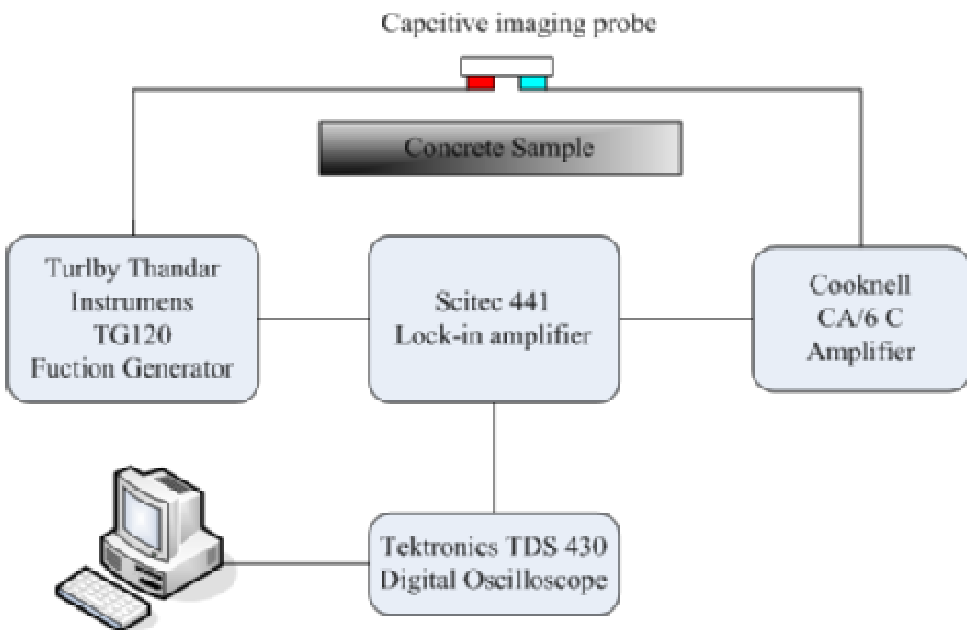


Figure A3-26 System block diagram of Capacitive imaging system.

A3.10.4 Results

Of available results, Figure A3-27 which shows a capacitive image of slightly corroded areas in a steel plate is most relevant.

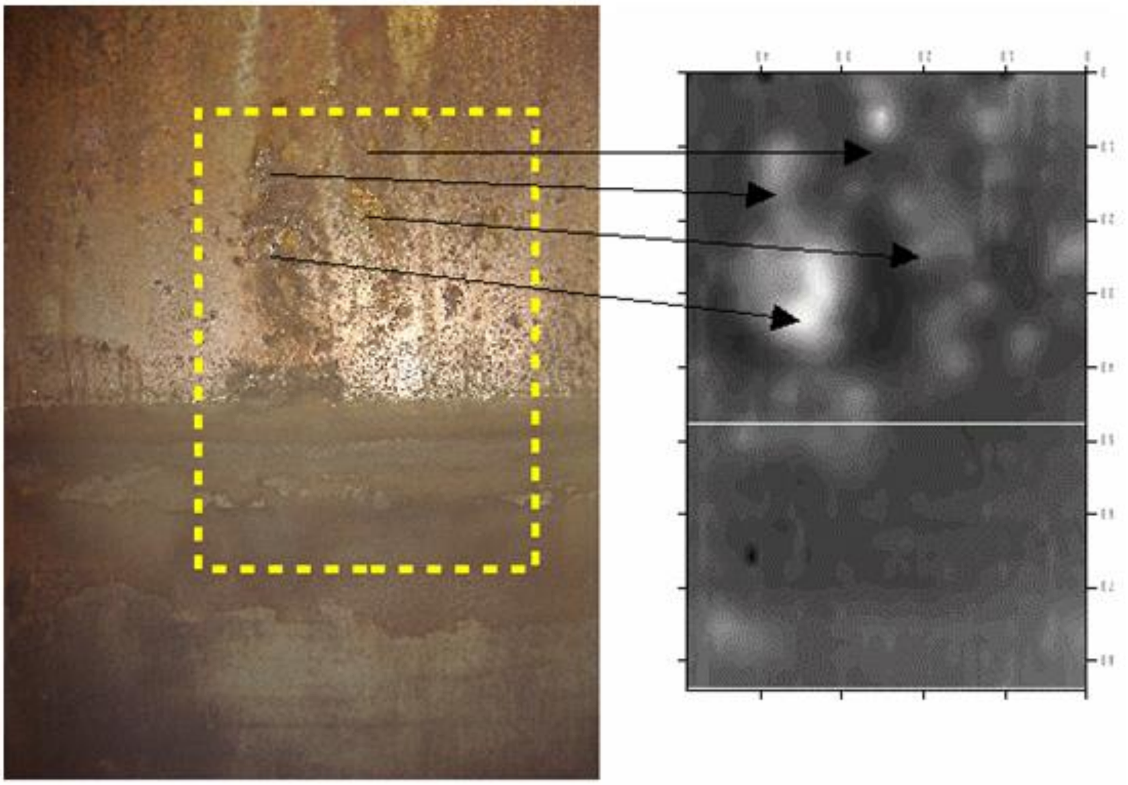


Figure A3-27 (a) Photograph of slightly corroded steel sample. (b) Capacitive image of the same sample, with corroded areas indicated.

It is not however clear what stand-off can be tolerated between the component and the sensors, nor what the effect would be of the insulation and metal cladding around a pipe.

A3.10.5 Status

The potential of this method for CUI inspection is not immediately evident from the available results. It is understood that this is a completed project (at the early stages of the RCNDE), which is not being actively developed for CUI or related applications.

A3.11 RCNDE CUI research projects

The following update was kindly provided by Professor Robert Smith, head of the RCNDE in October 2019.

Inspection of CUI, either in the presence of outer metallic cladding or not, features as a high priority in RCNDE's industrial-member vision for future research and a significant proportion of RCNDE's research pipeline (completed, current and proposed research) is relevant to this application.

Potentially applicable research is as follows.

- **Eddy-current tomography**, led by Prof Anthony Peyton at the University of Manchester and including the universities of Bristol, Warwick and Bath. A feasibility study has been completed and some projects are under way, with a significant new collaborative project proposed for the next RCNDE phase. This technology has the potential for inspection through insulation to determine the thickness of underlying metallic layers, particularly in the absence of a conducting outer cladding layer. This is an advanced development of the physical principles involved in the pulsed eddy-current method commonly employed for CUI.
- **Electrostatic** (including 'capacitive') methods have been studied by Prof David Hutchins and his team at the University of Warwick. There is potential for such a method to penetrate through various materials in order to inspect the structure below, including through an outer conducting layer. An early RCNDE project at Warwick on capacitive methods showed some potential for CUI inspection. See Appendix A3.10
- **Ultrasonic guided waves** have been researched by the Imperial College NDE Group (Prof Peter Cawley, Prof Mike Lowe, Dr Fred Cegla and Dr Peter Huthwaite) over many years and implemented for CUI using sensors placed on the pipe at one location under the cladding and inspecting many metres under the insulation from that location. The sensors can be deployed for the test and then removed or be permanently installed. More recent relevant work at Imperial College has included defect characterisation using distributed sensors, guided wave tomography and monitoring of defect growth rates as an improved indicator of long-term integrity. Work has also been done on EMAT transduction systems for permanent installation. Relevant spin-outs are Guided Ultrasonics Ltd and Permasense Ltd (now part of Emerson group). See Appendix A2.5.
- A **microwave** technique has been investigated at Imperial College for detecting water ingress under insulation (i.e. to identify areas at risk for external corrosion) using the combined cladding, insulation and pipe as a waveguide (see Appendix A3.3).
- **Wireless, permanently-installed, battery-free ultrasonic sensors,** originally developed by Prof Anthony Croxford and Prof Paul Wilcox at the University of Bristol (the 'WAND' system) have been developed further by a spin-out (Inductosense Ltd) with CUI being identified as a potential application. These are permanently installed ultrasonic sensors that can be triggered and interrogated inductively from a short distance such as through insulation.
- **Near Infra-red NDT** is being investigated by Prof David Hutchins at the University of Warwick. This has potential for detection and imaging of corrosion through some non-conducting coatings and insulation.
- **Novel high-sensitivity** Quantum-Well Hall Effect (QWHE) **magnetic sensors**, developed at the University of Manchester by Prof Mo Missous, have been shown to have significant benefits in certain inspection scenarios. In particular, QWHE sensors are applicable to situations where small magnetic-field variations due to defects are present at the sensor. This might aid large stand-off inspection such as in the CUI situation. The QWHE technology has the potential for thickness-mapping inspection

using 2D arrays for high-resolution imaging of the field from underlying metallic layers, even in the presence of a conducting outer cladding layer (Aluminium) using low-frequency pulsed eddy-current excitation. The relevant spin-out is Advanced Hall Sensors Ltd. which is conducting CUI feasibility studies using QWHE with the OTGC in Aberdeen on behalf of a large consortium of Oil and Gas companies.

- Specialist **electro-magnetic acoustic transducers** (EMATs) have been developed by Prof Steve Dixon and Dr Rachel Edwards at the University of Warwick for a range of applications. EMATs are applicable to inspection of corrosion under insulation in circumstances where the ultrasound generation in the metal is adequate, such as for sensors attached through the insulation or where the stand-off is non-conducting and not too thick. The relevant spin-out is Sonemat Ltd.