Annex D

NDE methods

D NDE Methods

Abbreviations:

ACFM:	Alternating Current Field Measurement
ACPD:	Alternating Current Potential Drop
AUBT:	Advanced Ultrasonic Backscattering Technique
ECA:	Engineering Critical Assessment
ET:	Eddy Current Testing
MT:	Magnetic Testing
PT:	Penetrant Testing
RT:	Radiography Testing
TOFD:	Time of Flight Diffraction
UT:	Ultrasonic Testing
VT:	Visual Testing
N.A:	non applicable
FBH:	Flat bottom Hole
SAFT:	Synthetic Aperture Focusing Technique

D.1 Introduction

At any point in the life cycle of a structure (e.g. design, fabrication, operation), it may be necessary to investigate whether it is fit to meet the service requirements for which it was intended, or which it will encounter in the future. An Engineering Critical Assessment (ECA) approach based on various rules of calculation can be used to answer to that question, and can cover a range of structures (e.g. pipelines, pressure vessels, bridges, tanks) and damage/failure mechanisms (fracture, fatigue, corrosion). The results of an E.C.A are generally expressed as a critical size that a defect (fatigue crack, corrosion …) shall not overcome.

There are many NDE methods, each with their specific capabilities and limitations. Some methods are only able to measure the length of the defect, while others also have capability to measure height of the defect. The methods also vary in their capacity to characterise a defect, i.e. to determine whether a defect is voluminous, planar, sharp etc. The different physical principals cause differences in performance on which the methods depend and the conditions of application.

When selecting a NDE method able to be applied for an ECA, a clear understanding of the principles of the method is essential. In other words when the physics of the method is understood then the shortcomings of the method will be appreciated. This will ensure that unrealistic criteria are not set and that blind faith in the outcome of NDE is avoided.

This document aims to provide guidelines to the mechanical engineer in order to provide him a basic knowledge of the possibilities and limitations of the NDE methods and techniques applicable on site in an industrial context in order to avoid such matters.

The main limitations and capabilities of NDE methods are given in Table D.1 to Table D.4 (from Ref 1)

Table D.1 – Generally accepted methods for the detection of accessible surface flaws

Material	NDE Method			
	VT	PT	MT	ET
Ferritic Steel	❖	❖	❖	❖ *
Austenitic Steel	❖	❖		❖ *

❖ * or ( ) indicates that the method is applicable with some limitations

Table D.2 - Generally accepted methods for the detection of internal flaws in full penetration welds

Material and type of weld	Parent material thickness/t (mm)		
	t ≤8	8 < t ≤40	t > 40
Ferritic butt-weld	RT or (UT)	UT or RT	UT or (RT)
Ferritic T-weld	(UT) or (RT)	UT or (RT)	UT or (RT)
Austenitic butt-weld	RT	RT or (UT)	RT or (UT)
Austenitic T-weld	(UT) or (RT)	(UT) or (RT)	(UT) or (RT)

Table D.3 - Detection and sizing capability of the main NDE methods

		NDE method					
		Visual inspection	Penetrant testing	Magnetic particle inspection	Eddy current	Radiograp hy	Ultrasonic testing
Detection Capability	Cracking (open to surface)	❖ *	❖	❖	❖	❖ *	❖
	Cracking (internal)	❖	❖	❖	❖	❖ *	❖
	Lack of fusion	❖	❖	❖	❖	❖ *	❖
	Slag/Inclusions	❖	❖	❖	❖	❖	❖
	Porosity/Voids	❖	❖	❖	❖	❖	❖
	Corrosion/Erosion	❖	❖	❖	❖	❖	❖
Sizing Capability	Flaw location	❖	❖	❖	❖	❖	❖
	Flaw length	❖	❖	❖	❖	❖	❖
	Flaw height	❖	❖	❖	❖ *	❖	❖
	Component thickness	❖	❖	❖	❖ *	❖	❖
	Coating thickness	❖	❖	❖	❖	❖	❖

* indicates that the method is applicable with some limitations

Table D.4 - NDE method versus damage type

Damage type	NDE method/technique	Capability/limitations
Corrosion/Erosion (Internal)	Visual Inspection (Vessels Only) – Internal	Good detection capability but requires internal access. Limited sizing capability (depth/remaining wall thickness).
	Manual Ultrasonic Testing/0° Probe – External	Generally good detection and sizing capability (can be poor if corrosion isolated, particularly the detection of pitting).
	Automated Ultrasonic Testing/0° Probe Mapping – External	Very good detection and sizing capability (application limited to pipe sections/vessel walls where simple manipulation can be facilitated). Corrosion maps allow accurate comparison of data between repeat inspections. Comparatively slow technique to apply.
	Continuous Ultrasonic Monitoring – External	Good detection and sizing capability (at specific monitoring locations).
	Profile Radiography (Piping Only) – External	Good detection and sizing capability but comparatively slow technique to apply.
Weld root Corrosion/Erosion	TOFD – External	Very good detection and sizing capability (depth/remaining wall thickness). Access to both sides of weld cap required.
	Manual/Automated Ultrasonic Testing/0° Probe – External	Good detection and sizing capability but requires extensive surface preparation i.e. removal of weld cap.
	Manual/Automated Ultrasonic Testing/Angle Probe – External	Detection and sizing capability but can be unreliable.
	X-ray tomography	Price technique for evaluating the extent and reason of the corrosion. Can be difficult to use on site
Hot Hydrogen Attack/HHA (Internal)	Ultrasonic Testing – External 0° Probe/High Sensitivity	Detection capability/base material but can give false indications. Use of mapping system facilitates monitoring. For welds, removal of cap is required.
	AUBT - External	Very efficient for base material but request skill operators and appropriate procedures
	Angle Probe(s)/Medium Sensitivity	Detection capability/welds but cannot detect microscopic stages of HHA. Use of automated system facilitates monitoring of macro-cracking.
	TOFD - External	Detection capability/welds although discrimination between micro-cracking and other weld defects a problem. However, establishment of a base-line facilitates monitoring of micro-cracking.

Table D.5 - NDE method versus damage type

Damage type	NDE method/technique	Capability/limitations
Hydrogen Pressure Induced Cracking (HIC, Stepwise Cracking)	**Ultrasonic Testing – External** - 0° probe - 45° angle probe	Good detection at later stages, but there are no proven early warning (susceptibility to cracking) tests for on-site inspection.
Creep Damage	**Surface Testing**	Magnetic measurements of Barkhausen noise, Differential Permeability or Coercivity are possible but also affected by other parameters e.g. stress and heat treatment. Surface Replication can be used to examine microstructure. Hardness measurement is also used for quick evaluation, but lifetime assessment requires combination with other techniques.
	UltrasonicTesting - Attenuation/loss of back wall echo - Backscatter - Velocity measurement	Methods developed for detection of early stages have not been proven in the field. Standard ultrasonic testing techniques are suitable at later stages. Ultrasound is also used for magnetite layer measurements, which is used for operational temperature estimation. Conventional measurements, and laser profilometry, are used for determining and quantifying creep deformation (swell or expansion
	Small scale test	The miniature samples extraction and destructive test of such miniature specimens is used for post exposure creep status determination. Techniques most used are miniature creep test, small punch test and indentation test
	X-ray diffraction	This technique has been used for stress and grain size calculation in laboratory. At present effort to adapt it for in field measurement are on-going

Table D.6 - NDE method versus damage type

Damage type	NDE method/technique	Capability/limitations
Fatigue Cracking (Internal/External)	Magnetic Particle Testing	Good detection capability but requires access to fatigue crack surface. Good length sizing capability. Some surface preparation usually required.
	Penetrant Testing Eddy Current	As above, for non-magnetic materials.
	Ultrasonic Testing/Angle Probe(s)	Good detection and sizing capability (length and height), enhanced by use of automated systems –
	TOFD	TOFD gives very accurate flaw height measurement and allows in-service crack growth monitoring.
	ACFM (can be used in-lieu of surface techniques stated above)	Good detection capability but requires access to fatigue crack surface. Length and some depth sizing capability. Unlike Magnetic Particle does not usually require surface preparation and can be used through coatings. Better for inspecting welds than Eddy Current.
	X-ray tomography	Good detection capability. Excellent for sizing but can be difficult to apply on site
Stress Corrosion Cracking/SCC (Internal/External)	Surface Testing	Penetrant / Magnetic Particle (not austenitic)/Eddy Current (not ferritic) techniques - Good detection capability but access required to crack surface. Techniques require plant shutdown.
	Ultrasonic Testing – External	Fair detection capability - can be used on-line. Specialist techniques have some capability to determine crack features (orientation and dimensions (inc. height)).
	TOFD	TOFD can provide very accurate flaw height measurement and allows in-service crack growth monitoring.
	X-ray tomography	Good detection capability. Excellent for sizing but can be difficult to apply on site
	Acoustic Emission – External	On-line detection of growing SCC in large component systems too complex to be inspected by other techniques. Extraneous system noise can produce false indications.
	ACFM	ACFM has been used for detection of SCC (external). In particular, it was used to locate clusters of severe SCC under protective coating on a pipeline. However, the complex nature of the cracking means it is usually not possible to depth size the defects.

Table D.7 summarises the field of application of NDE methods and techniques (see appendix 1 for description, limitations, advantages and drawbacks) able for sizing defects.

Name	Abbreviation	Surface defect detection	Embedded defect detection
Visual testing	VT	Yes	No
Manual Ultrasonic Testing	M UT	Yes	Yes
Automatic Ultrasonic Testing	A UT	Yes	Yes
Time of Flight Diffraction	TOFD	Yes	Yes
Radiography Testing	RT	Yes	Yes
Magnetic Testing	MT	Yes – restricted to ferromagnetic materials	No - limited to a depth of 2 to 3 mm in the best conditions on ferromagnetic materials by using permanent magnet
Penetrant Testing	PT	Yes	No
Eddy current testing	ET	Yes	No in ferromagnetic material without saturation device – limited to the depth of penetration of the current at the probe frequency
Alternating Current Field Measurement	ACFM*	Yes	No in ferromagnetic material without saturation device* – limited to the depth of penetration of the current at the probe frequency
Alternating Current Potential Drop	ACPD	Yes	No

*Note * : ACFM shares the same restriction caused by the skin effect as eddy current testing. Therefore, ACFM could in principle also be used to detect near surface buried defects in non-ferromagnetic metals (or in ferromagnetic metals using a saturation method but it is not well-established, and so not encouraged. However, operators are taught what signal a sub-surface defect produces in case they come across one.)*

Table D.7 - Field of application of NDE methods

Name	Abbreviation	Surface defect detection	Embedded defect detection
Visual testing	VT	Yes	No
Manual Ultrasonic Testing	M UT	Yes	Yes
Automatic Ultrasonic Testing	A UT	Yes	Yes
Time of Flight Diffraction	TOFD	Yes	Yes
Radiography Testing	RT	Yes	Yes
Magnetic Testing	MT	Yes – restricted to ferromagnetic materials	No - limited to a depth of 2 to 3 mm in the best conditions on ferromagnetic materials by using permanent magnet
Penetrant Testing	PT	Yes	No
Eddy current testing	ET	Yes	No in ferromagnetic material without saturation device – limited to the depth of penetration of the current at the probe frequency
Alternating Current Field Measurement	ACFM*	Yes	No in ferromagnetic material without saturation device* – limited to the depth of penetration of the current at the probe frequency
Alternating Current Potential Drop	ACPD	Yes	No

*Note * : ACFM shares the same restriction caused by the skin effect as eddy current testing. Therefore, ACFM could in principle also be used to detect near surface buried defects in non-ferromagnetic metals (or in ferromagnetic metals using a saturation method but it is not well-established, and so not encouraged. However, operators are taught what signal a sub-surface defect produces in case they come across one.)*

Only techniques based on ultrasound or radiation are able to detect and consequently to size embedded defects. Eddy currents on the material tested and of the probe frequency.

Table D.8 gives an estimation of these values for various material

Table D.8 - Estimated depth of eddy current penetration at 20 KHz

Material	Depth of penetration (mm)	Material	Depth of penetration (mm)
Graphite	8	Aluminium alloy	1
Titanium	6	Copper	0.6
Stainless steel	3.5	Carbon Steel	0.15
Zirconium	2 mm	Cast Iron	0.07

Acoustic emission and thermography can be used for labs application to detect crack initiation and propagation phenomenon but without any quantification. Acoustic emission and optical techniques (interferometry, shearography …) can be used on site for in service structure monitoring.

Ultrasonic techniques can be used for testing austenitic welds but require the application of specific procedures after to have verified the possibility of ultrasonic propagation in the concerned weld and a satisfactory signal to noise ratio. Some alloys such Inconel 316L can be found difficult to test. The values given in the tables concerning the accuracy of length and height may be not reached for austenitic welds.

D.2 Comparison of NDE efficiency for length evaluation on site conditions

D.2.1 Introduction

There are a lot specific ultrasonic techniques not possible to list in these tables. Rayleigh waves can be successfully applied on labs application for monitoring crack growing. Cracking in coarse grain materials can be difficult to detect and consequently to size with ultrasonic techniques. SAFT and Phased Array can improve Signal to Noise ratio in that case. EMAT can be found very useful at hot temperature. It should be kept in mind that transit ultrasonic time shall be measured when height sizing is pursued. Amplitude base ultrasonic technique can be useful to assess small defects but can provide only estimation.

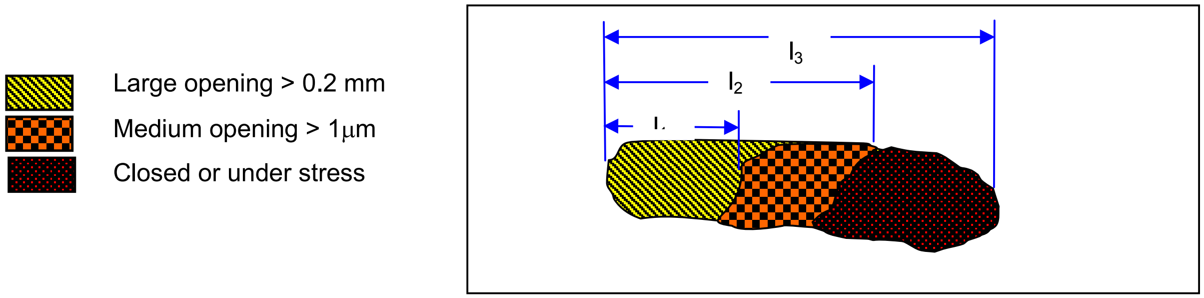
Tight fatigue cracks can be not detected. Branches cracks can produce artefacts.

Table D.9 to Table D.14. compare efficiency of the more common NDE techniques available for sizing (length and height) cracks. The values mentioned in the tables are indicatives and given for ferritic materials. These values depends on the procedure applied and can be influenced by many parameters such: surface roughness and geometry, depth location versus surface access available to perform the NDE inspection, orientation, opening, faces morphology, branching occurrence, metallurgical features (welded zone, grade, anisotropy, ….) The Δ value given in these tables indicates the minimum growing gap (in length or in height) necessary to be able to conclude to a possible crack evolution between two periodical NDE inspections.

Whatever the NDE technique applied, it is strongly recommended, when no relevant NDE data are available on the application case, to calibrate the technique on known artificial and/or natural defects representative of the application

D.2.2 Comparison of NDE efficiency for length evaluation on site conditions based on “expert judgment”

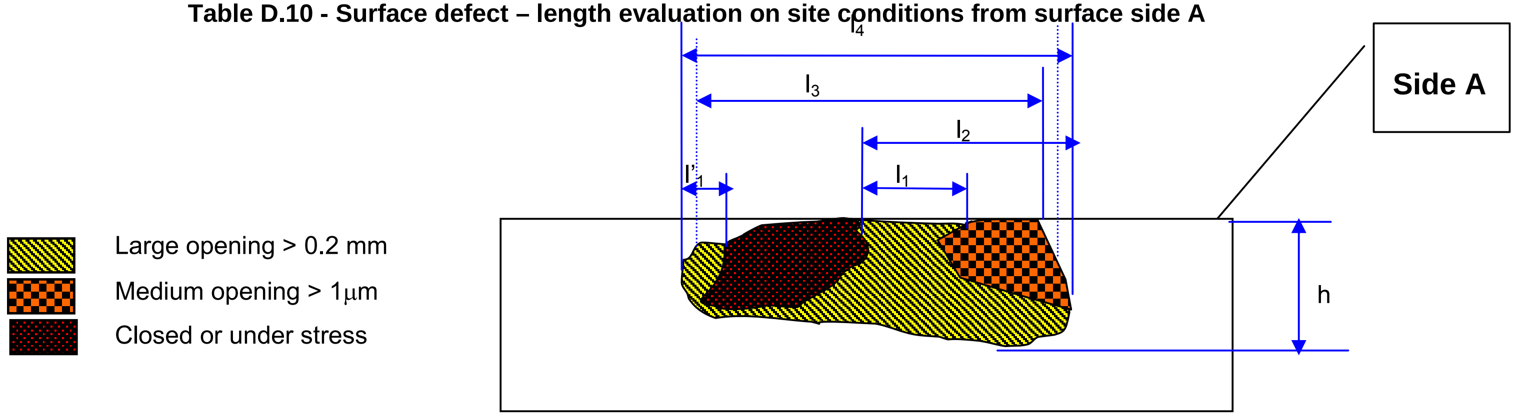
Table D.9 - Embedded defect - length evaluation on site conditions



	Visual testing	Manual UT	Automatic UT	TOFD	RT	MT	PT	Manual ET	A.C.F.M	ACPD
Measured value	N.A.	l_2	l_2	l_2	$l_1 < l < l_2$	N.A.	N.A.	l_3 ?	N.A.	N.A.
Repeatability (± mm)	N.A.	5	2	2	2	N.A.	N.A.	5	N.A.	N.A.
Standards		EN 1714	ASTM ??	In progress	EN 1435					
Acceptance levels		EN 1712		In progress	EN 12517					
Limits of detection (indicative value)		FBH 1 mm	FBH 0.5 mm	Porosity 0.3 mm	1% of t in the best conditions with X-rays			The defect shall be contained in the depth of penetration of the current and used on smooth surface		

Note : N.A means Non Applicable and FBH : Flat Bottom Hole

Table D.10 - Surface defect – length evaluation on site conditions from surface side A

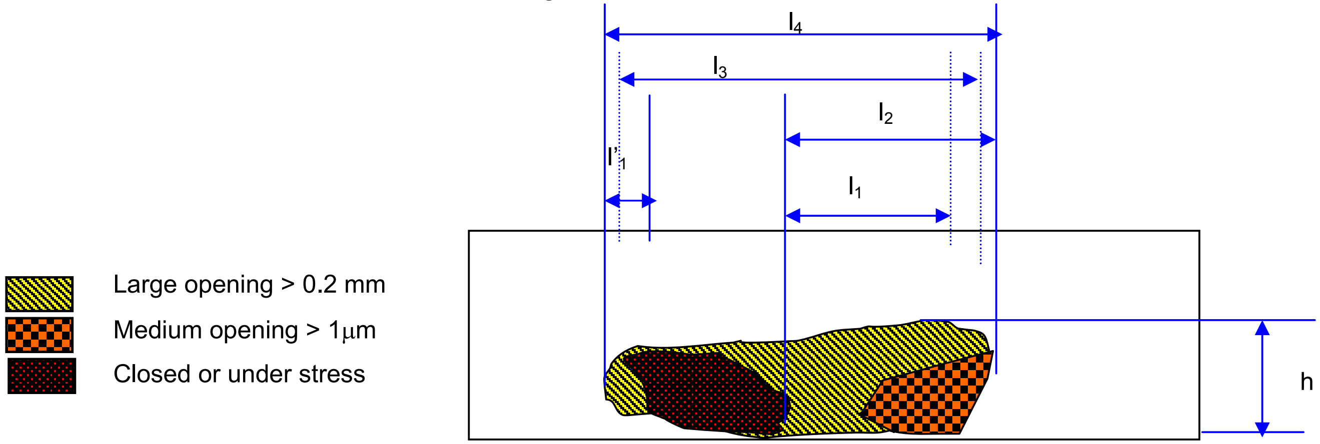


	Visual testing	Manual UT	Automatic UT	TOFD	RT	MT	PT	Manual ET	A.C.F.M
Measured value	l_1 (#)	l_2 & l'_1	l_2 & l'_1	l_2 & l'_1	$l_1 < l < l_2$ & l'_1	l_2 & l'_1	l_1	l_2 & l'_1	l_2 & l'_1
Δ (± mm)	2 (#)	5	2	2	2	2	2	5	5
Standards		EN 1714	ASTM E 1961-98	XP-TS 14751	EN 1435	EN 1290	EN 571-1	EN 1711	French COFREND Recommendation
Acceptance levels		EN 1712		In progress	EN 12517	EN 1291	EN 1289		
* Minimum height to allow sizing		h > 0,5mm	h > 0,5mm	h > 1 mm	h > 1% t	h > 0,5mm	h > 0,2mm	h > 0,5mm	h > 1mm

* These values are only indicatives and depend mainly on surface conditions, material type and grade, operating conditions.

Only applicable for cracks having a large opening with appropriate lighting

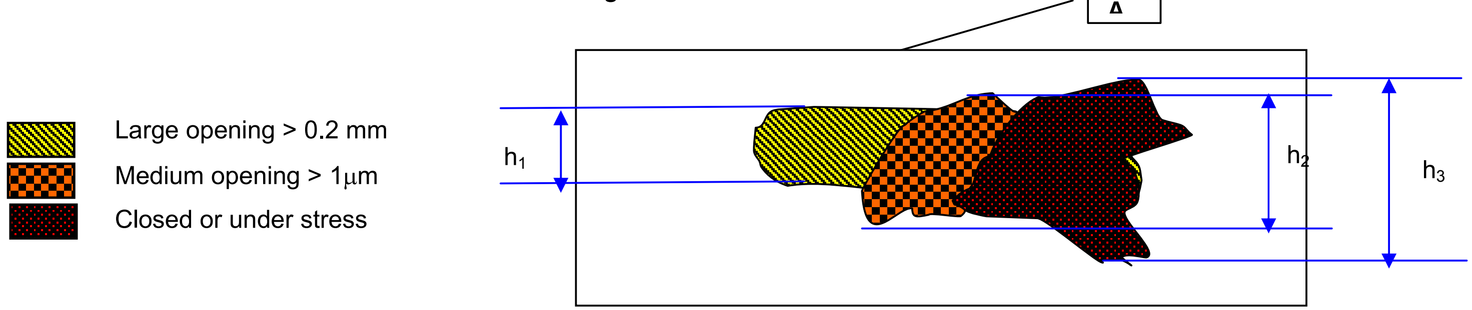
Table D.11 - Root defect – length evaluation on site conditions from side A



	Visual testing	Manual UT	Automatic UT	TOFD	RT	MT	PT	Manual ET	A.C.F.M
Measured value	N.A.	l_2 & l'_1	l_2 & l'_1	l_2 & l'_1	$l_1 < l < l_2$ & l'_1	N.A.	N.A.	$l_1 < l < l_2$ & l'_1	N.A.
Δ (± mm)	N.A.	5	2	2	2			5	N.A.
Standards		EN 1714	ASTM E 1961-98	XP-TS 14751	EN 1435			EN 1711	French COFREND Recommendation
Observations								The defect shall be contained in the depth of current penetration.	

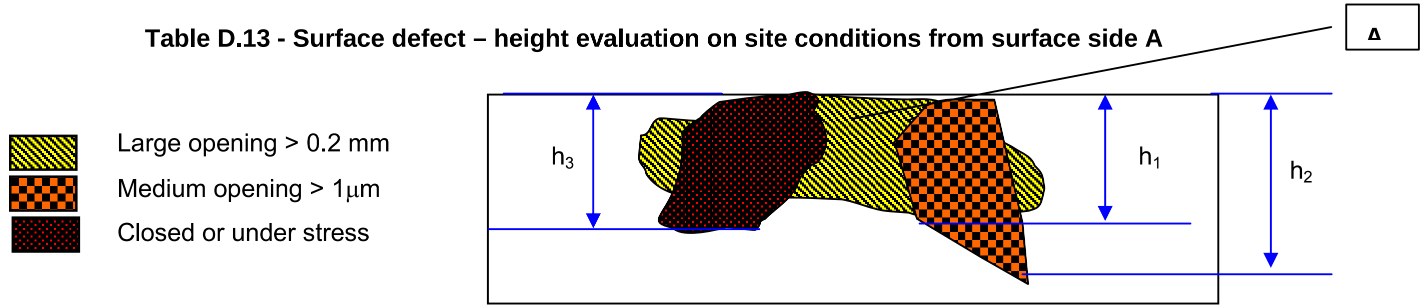
D.2.3 Comparison of NDE efficiency for height evaluation on site conditions

Table D.12 - Embedded defect - height evaluation on site conditions



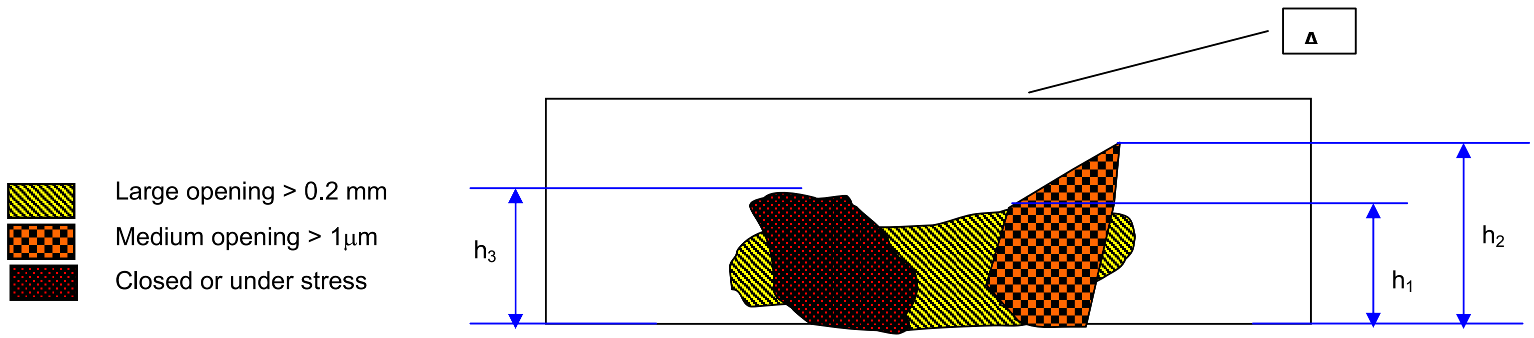
	Manual UT	Automatic UT	TOFD	RT	MT	PT	Manual ET	A.C.F.M
Measured value	Not actual value is measured with conventional manual UT	h_1 , h_2	h_1 , h_2	Not possible with standard techniques . Specific techniques such parallax …can be used X-ray tomography can be applied	N.A	N.A	Depends on material and procedure	
Δ (± mm)	Depends on procedure	1	1	Depends on procedure			Depends on material and procedure	
Standards	EN 583-5	No standard for height sizing	XP-TS 14751	No standard for height sizing				
Observations	Request specific procedures and skill operator	Depends on component thickness, probe frequency …	Depends on component thickness, probe frequency	Specific procedures requested Only for particular application. Difficult to apply on site			The defect shall be contained in the depth of current penetration.	

Table D.13 - Surface defect – height evaluation on site conditions from surface side A



	Manual UT	Automatic UT	TOFD	RT	MT	PT	Manual ET	A.C.F.M
Measured value	Specific procedures requested	h_1 , h_2	h_1 , h_2	Specific procedures requested	N.A	N.A	Possible but request calibration on defect and/or notches of known height	h_2 , If the defect is really as oddly shaped as on the sketch (highly non-elliptical), the depth will be underestimated.
Δ (± mm)	Depends on the procedure	Depends on the procedure	0,5	Depends on the procedure used				0,5 or 10% (whichever is largest)
Standards	EN 583-5	No standard for height sizing	XP-TS 14751	No standard for height sizing			No standard for height sizing	
Minimum height for sizing (indicative value)		1 to 2 mm	1 to 2 mm					
Observations	Request specific procedures and skill operator	Depends on component thickness, probe frequency …	Depends on component thickness, probe frequency Lateral wave erasing process may be used to reduce this limitation	Only possible with specific procedures and on particular application. Difficult to apply on site			The defect shall be contained in the depth of current penetration.	Table exists only for ferromagnetic material – model based on semi-elliptical defect

Table D.14 - Root defect – height evaluation on site conditions from surface side A



	Manual UT	Automatic UT	TOFD	RT	MT	PT	Manual ET	A.C.F.M
Measured value	Specific procedures requested		h_1 , h_2	Specific procedures requested	N.A	N.A	To assess by calibration	N.A
Measured value								
Repeatability (± mm)	Depends on the procedure	0,5	0,5	Depends on the procedure				
Standards	EN 583-5	Not for height sizing	XP-TS 14751	Not for height sizing			Not for height sizing	
Standards								
Observations	Only possible with specific procedures	h > 1 mm	h > 1 mm	Only possible with specific procedures			Only if defect is within depth of current penetration	

D.3 Field of application of NDE methods and techniques for corrosion assessment

A detailed description of the NDE techniques able to detect corrosion is given in Appendix 1. The following

Table D.15 gives a comparison of the possibilities of these techniques versus the different types of corrosion

Technique	Crevice Straight pipes	Pits	Erosion-Corrosion In bend	Corrosion under Support	Leak
RT	✓	✓ X-rays requested	✓	/	/
Manual	✓	With specific probes and	✓ Thickness measurement	/	/
Thermography		/	/	/	✓ Detectable if the lea a variation of surf
Guided waves	✓	/	/	✓ Possible by comparison between two inspections	If induced by a r corrosion
UT Multiskips LORUS, CHIME	✓ At a maximum distance of 1 m			✓ Possible – depends on support type	
TOFD	✓	✓		✓ Possible – depends on support type	
Pulsed Eddy Current	✓		✓ very accurate with relative measurement		

that can happen. In that table √ means that the insulation shall be removed from the inspection area.

Table D.15 - Scope comparison of the potential of NDE techniques versus the corrosion type

Technique	Crevice Straight pipes	Pits	Erosion-Corrosion In bend	Corrosion under Support	Leak	Corrosion near a weld
RT	✓	✓ X-rays requested	✓	/	/	✓
Manual	✓	With specific probes and	✓ Thickness measurement	/	/	✓
Thermography		/	/	/	✓ Detectable if the leak induce a variation of surface T°	/
Guided waves	✓	/	/	✓ Possible by comparison between two inspections	If induced by a major corrosion	
UT Multiskips LORUS, CHIME	✓ At a maximum distance of 1 m			✓ Possible – depends on support type		✓ At a maximum distance of 1 m
TOFD	✓	✓		✓ Possible – depends on support type		✓
Pulsed Eddy Current	✓		✓ very accurate with relative measurement			

D.4 Flaw detection, sizing and NDE (Non-Destructive Evaluation) capabilities

D.4.1 Scope

Inspection procedures are made up of a mix of NDE techniques, setting procedures or calibrating principles, decision steps, scanning systems, recording and illustration tools and software. They often involve a process of interpretation of indications which relies on the skill of the operator. As a result they cannot be considered simply as measurements and NDE performance for detecting, locating, classifying and sizing defects cannot be represented by simple confidence intervals.

To be able to use NDE inspection data in a structural integrity assessment it is essential to establish whether all the defects above a certain size were detected and reported and how precise the given sizes in depth and in length are. Guideline performance values which have been derived from analysis of specific blind test results or from parametric studies conducted by independent institutions are presented in this section.

It is important to clarify the terminology used to understand the meaning of NDE evaluations and to use reliability data correctly for structural integrity assessment purposes. Reliability (R) of NDE-based inspection procedures is considered to consist of three key elements.

$$R = f\left(IC\right) - g\left(AP\right) - h\left(HF\right) \qquad \text{(D.1)}$$

where IC = intrinsic capability of techniques/procedures

AP = limitations imposed by the specific application

HF = human factors

Effectiveness of the inspection can be defined as:

$$E = f\left(IC\right) - g\left(AP\right) \qquad \text{(D.2)}$$

This section considers mainly inspection effectiveness.

D.4.2 Definitions and terminology

Defect Types

Flaws can take many forms but NDE effectiveness assessments refer chiefly to planar type defects, approximately perpendicular to the surface (tilt angle ±30°). To detect and size these correctly specific NDE techniques are required or the usual (ASME type ed. I986) techniques have to be set at a high level of sensitivity or cut off: 20 or even 10% DAC. This leads to many indications and also to false calls. This class of defects, which are homogeneous only from an NDE point of view, are referred to as PPD (perpendicular planar defects) and cover lack of fusion and cracks arising due, for example, to mechanical fatigue, thermal fatigue, corrosion and reheat cracking.

The present compilation is limited to PPD defects with a through wall size larger than 5% of the wall thickness (*t*). Although volumetric defects can also be used for effectiveness evaluations, they are not included here since detection and sizing performance of NDE procedures is often better such defects than for PPDs.

NDE Performance Levels

Inspections can be conducted at different “quality” or performance levels.

The present compilation considers two different levels:

- **Q level** fixed by Qualification according to the European Methodology which fixes the effectiveness of the inspection procedure at a level considered possible after capability evaluation.

- **B level** (Blind tests) corresponding to what was achieved by 60% of the inspection procedures applied in round-robin trials relevant to the situation considered. Effectiveness can be very good with high performance inspection procedures but also very poor with low performance procedures even if applied with care by a good team. Within this level two sub-sets are considered: 'good practice' and 'low capability'.

Performance Parameters

The following parameters are used in assessing NDE performance:

FDP: false detection performance of an inspection team or procedure for a given population of defects

CRP: correct rejection performance of defects to be rejected by the inspection procedure, according to the ASME acceptance/rejection criteria (often around 10% of the wall thickness)

MESD: mean error of sizing in depth

SESD: standard deviation of sizing error in depth

MESL: mean error of sizing in length

SESL: standard deviation of sizing error in length

FCRP: false call rate leading to erroneous rejection

D.4.3 Condensed NDE effectiveness data

To give an indication of NDE effectiveness it is necessary to condense the information previously assembled into a limited number of figures and data tables. For this reason only two groups of components are considered in detail.

<u>Ferritic steel piping (5 mm $\leq t \leq$ 50 mm)</u>

Figure … provides an example of the variation in capabilities of ultrasonic inspection. a) shows results expected from procedures qualified to reasonably attainable targets for detection and sizing. b) pertains to 'good practice' procedures subjected to qualification, while c) shows results from low capability (but still commonly applied) procedures, or due to unconsidered environmental or human effects.

<u>Austenitic steel piping (5 mm $\leq t \leq$ 30 mm)</u>

Figure … presents a similar overview for wrought austenitic components, which is also appropriate for welds in castings. As a benchmark a defect size of 40% *t* is used, indicating acceptable sentencing capability for 'good practice' procedures. However 100% success is never obtained.

D.4.4 Input data for structural integrity assessment

a) Using inspection qualification

Providing:

- inspection targets are clear and used to define targets or levels of qualification,
- such targets are acceptable for some procedures (as shown by exercises or previous evaluations), and
- qualification can be performed with all the necessary elements to provide the operator with a procedure known for its capability (European Methodology)

Then it is straightforward to provide the structural integrity engineer with an objective measure of inspection capability (or effectiveness, if relating it to a specific application).

It appears reasonable to declare that, if no defect that is deeper than 40% t is found by these high effectiveness inspection procedures then no such defect exists in the component.

b) Not using inspection qualification

Probabilistic assessment of the data for defects smaller than 40% t is possible but of limited realism in practice since no input data exist prior to inspection about the defect distribution in different components after fabrication and after service. If inspection is performed using non-qualified procedures, it is not possible to exclude the presence of a defect of depth < 75% t. In contrast, using qualified procedures, probabilistic approaches can be used for defects in the range $0 \leq t \leq 40\%$.

D.4.5 Summary

A point to note is that most levels of inspection often range between 'good practice' and 'low capability'. Table …. summarises the types of components for which data are available. Table ….. provides information on the parameters MESD, SESD, MESL and SESL for those nine component types when they contain planar flaws of depth equal to 40% of the wall thickness. In particular, the values of mean error and standard deviation of error in the depth sizing provide useful quantitative values for consideration when defining the appropriate inputs for flaw depth in an assessment.

Table D.16 - Categorisation of Component Types

Category	Description	Material	*t* (mm)	D (mm)
1	Heavy pressure vessel (or flat plates)	carbon steel	>75	-
2	Heavy section piping (or flat plates)	carbon steel	30 - 75	>250
3	Thin section piping (or flat plates)	carbon steel	10 - 30	>250
4	Small diameter piping	carbon steel	5 - 30	50 - 250
5	Heavy section piping	as wrought	>30	>250
6	Small diameter piping	as wrought	<30	50 - 250
7	Heavy section piping (or elbow)	as cast	20 - 80	>250
8	Dissimilar metal zones (piping or comp.)	Various	20 - 80	>250
9	Small tube (steam generators)	as wrought	1 - 5	20 - 50
10	Small tube (heat exchangers)	carbon steel	1 - 5	30 - 50
11	Thin flat plate	alloys	<5	-

cs : carbon steel   as : austenitic steel   *t* : thickness   D : pipe internal diameter

Table D.17 - Summary of Ultrasonic Inspection Capabilities for Planar Flaws of Depth Equal to 40% Wall Thickness

Ultrasonic Inspection Class	Component Classification	MESD (mm)	SESD (mm)	MESL (mm)	SESL (mm)	*t* (mm)
Good practice and qualified procedure (aQ)	1	3	5	3	10	>75
	2	1	3	5	3	30 - 75
	3	1	3	2	5	10 - 30
	4	2	3	5	10	5 - 30
	5	0	5	-5	12	>30
	6	0	2	-3	10	<30
	7	0	5	0	20	20 - 80
	9	-	-	0(1)	4(1)	1 - 5
Good practice and non-qualified procedure (aB)	1	5	20	5	50	>75
	2	5	15	5	20	30 - 75
	3	3	5	5	10	10 - 30
	4	3	5	5	10	5 - 30
	5	-2	5	-10	25	>30
	6	-2	3	-10	25	<30
	7	2	6	0	25	20 - 80
	9	-	-	-3(2)	9(2)	1 - 5
Low effectiveness and non-qualified procedure (bB)	1	-7	15	-30	50	>75
	2	-5	15	-20	30	30 - 75
	3	-3	10	-5	20	10 - 30
	4	-3	10	-5	15	5 - 30
	5	-4	7	-10	40	>30
	6	-4	5	-20	20	<30

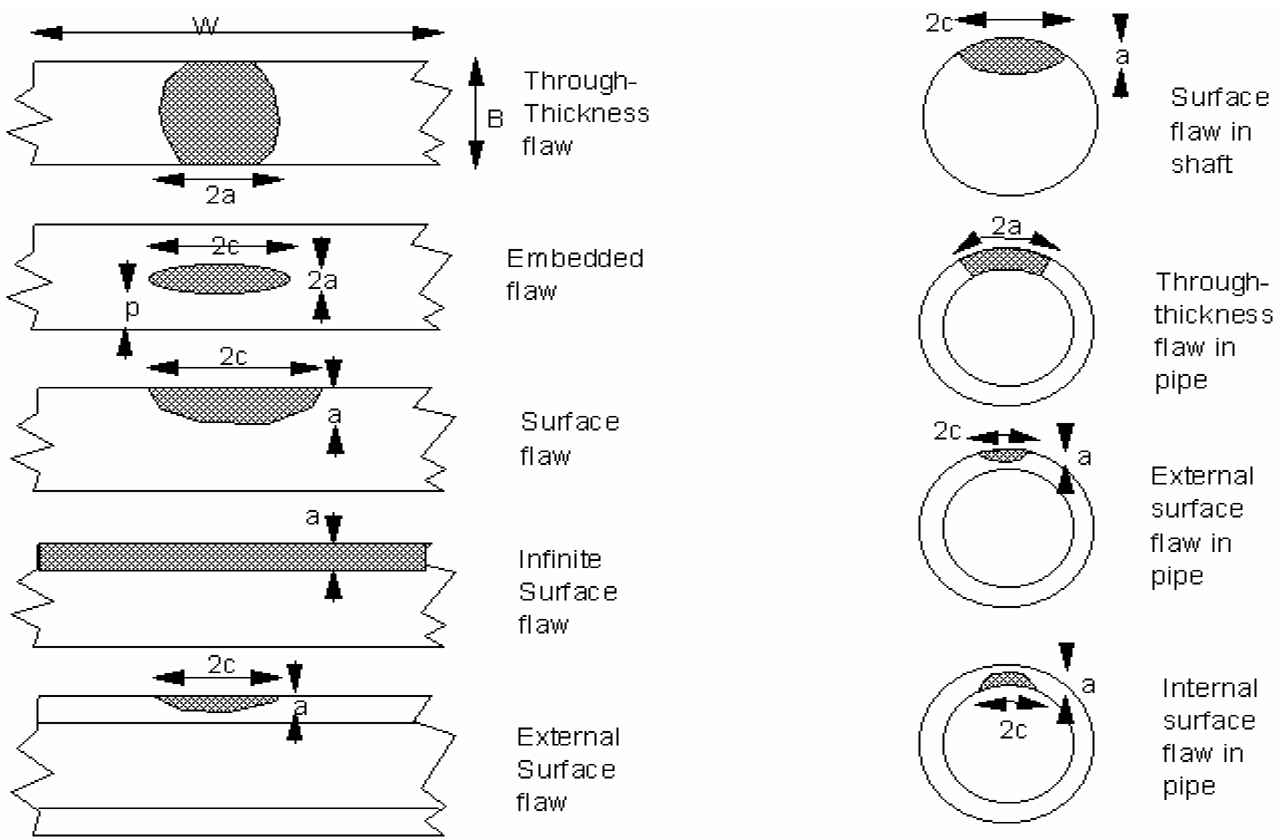


Figure D.1 - Definition of Flaw Dimensions for Common Component Geometries

Figure D.2 – Criteria for Interaction of Flaws in Collapse – Dominated Cases

D.5 Reliability / Probability aspects of NDE

When used as an input parameter in the FITNET analysis the potential error in the flaw size determined in a non-destructive inspection (NDE) has to be taken into account. An appropriate measure for this is the coefficient of variation (CoV) which refers to the ratio of standard deviation and mean value. For the use in FITNET FFS Procedure (Annex H) this is based on a normal distribution for the crack depth dimensions a or c (respective c for through-wall and edge cracks). The sizing error depends on the NDI technique, on the skill of the operator with respect to the testing device as well as to the structure to be inspected, to component geometry and material, accessibility of the defective site and other factors. The size of a recorded flaw is usually established by the operator, often not following rigorous reasoning that could be documented. The NDI data used by the structural integrity engineer will always be the result of a complex combination of various information and decisions taking during the process generating this information [Dillström & Nilsson, CSI]. This makes it an extremely difficult task to establish realistic COV values for NDE crack sizes. Whilst no recommendations on data to be used for a special case can be made some typical sizing errors are given in Table EXXfor ultrasonic testing (UT) and a crack depth-wall thickness ratio of 0.4.

Table D.18 - Typical Sizing Errors for NDE Methods

Component type	Material	NDI technique	Sizing error (crack depth) in mm
Plate (wall thickness: > 75 mm)	Ferritic steel	Advanced UT Good practice UT Low effectiveness UT	5 12 15
Pipe (wall thickness: 30-75 mm) (diameter > 250 mm)	Ferritic steel	Advanced UT Good practice UT Low effectiveness UT	5 15 15
Pipe (wall thickness: 10-30 mm) (diameter >250 mm)	Ferritic steel	Advanced UT Good practice UT Low effectiveness UT	3 5 10
Pipe (wall thickness: 5-30 mm) (diameter 50-250 mm)	Ferritic steel	Advanced UT Good practice UT Low effectiveness UT	3 5 10
Pipe (wall thickness: > 30 mm) (diameter > 250 mm)	Wrought austenitic steel	Advanced UT Good practice UT Low effectiveness UT	5 5 7
Pipe (wall thickness: < 30 mm) (diameter 50-250 mm)	Wrought austenitic steel	Advanced UT Good practice UT Low effectiveness UT	2 3 5

NOTE Flaws can take many forms but NDI effectiveness assessments refer chiefly to planar type defects, approximately perpendicular to the surface (tilt angle ±30°). To detect and size these correctly specific NDI techniques are required or the usual (ASME type ed. I986) techniques have to be set at a high level of sensitivity or cut off: 20 or even 10% DAC. This leads to many indications and also to false calls. This class of flaws, which are homogeneous only from an NDI point of view, are referred to as PPD (perpendicular planar defects) and cover lack of fusion and cracks arising due, for example, to mechanical fatigue, thermal fatigue, corrosion and reheat cracking. The compilation given in Table xx is limited to PPD defects with a through wall size larger than 5% of the wall thickness. Although volumetric flaws can also be used for effectiveness evaluations, they are not included here since detection and sizing performance of NDI procedures is often better such defects than for PPDs.

D.6 Description of NDE methods - Introduction

This appendix is compiled with parts extracted from the TNO reports –blue lines (Ref2) and the HSE report – orange lines (Ref 1)

There are many NDE methods, each with their specific capabilities and limitations. Some methods are only able to measure the length of the defect, while others also have capability to measure height of the defect. The methods also vary in their capacity to characterise a defect, i.e. to determine whether a defect is voluminous, planar, sharp etc. The different physical principals cause the differences in performance on which the methods depend and the conditions of application.

When selecting a NDE method able to be applied for an ECA, a clear understanding of the principles of the method is essential. In other words when the physics of the method is understood then the shortcomings of the method will be appreciated. This will ensure that unrealistic criteria are not set and that blind faith in the outcome of NDE is avoided.

Short descriptions of a number of NDE methods including the physical principals and applications are given in this annex.

D.7 NDE for general application

D.7.1 Visual inspection

D.7.1.1 Description

Visual inspection is the oldest form of inspection. It may be performed by the naked eye or by aid of tools such as magnifying glasses, mirrors and endoscopes.

D.7.1.2 Applications

It is only used for the detection of surface defects, such as cracks, casting defects, corrosion, machining defects etc. Inspection may be performed both from the outside and, with the aid of specialised tools such as endoscopes, from the inside of constructions such as bores and cavities. However, detection is limited to surface-breaking defects and often additional NDE (such as magnetic particle inspection, liquid penetrant testing or eddy current inspection) is required to enhance the probability of detection for expected defects mainly during In Service Inspections, or to comply with the fabrication specifications.

D.7.1.3 Inspection results

Visual inspection shows the shape and extent of surface anomalies. Since only the surface is viewed, in the case of a linear indication of a crack only the indication length can be measured. In the case of non-linear indications, the defect area can also be measured. Note, if the surface is too heavily ground when preparing it for inspection,, material can be smeared over the defect causing its concealment.

D.7.2 Magnetic testing (MT)

D.7.2.1 Description

There are several techniques, which are used depending on the defects that need to be detected and the sensitivity required.

Magnetic Testing (MT) is in principle a surface inspection technique, just like visual inspection. The portion of a defect that is just below the surface also contributes to the signal. The method relies on the distortion of magnetic flux lines by defects present in the material under inspection, causing leakage of the flux outside the material.

In the case of magnetic particle inspection, a powder or liquid containing particles that can be magnetised is spread over the surface of the object. The particles in the fluid concentrate in the region of magnetic flux leakage signalling surface breaking defects. This results in indications of cracks, which may be visually detected. Often contrasting white paint or fluorescent particles are used to increase detectability.

D.7.2.2 Applications

It is used for detection of surface cracks in or close to welds and in forged or moulded steel objects. Applicability is limited to homogeneously magnetisable materials. Application to high alloy (magnetisable) materials such as duplex steel is not advisable, due to the potential occurrence of spurious indications.

D.7.2.3 Inspection results

It is similar to visual inspection, in that only the defect dimensions on the object's surface can be measured such as the length of linear indications and area of non-linear indications. Crack depth cannot be measured. Distinction can be made between linear and non-linear surface breaking indications.

D.7.3 Penetrant testing (PT)

D.7.3.1 Description

Liquid (or dye) penetrant inspection is a surface inspection method. Defects are detected through capillary accumulation of liquids in cracks. Therefore the crack must be open at the surface in order to be detectable. s. A coloured or fluorescent liquid is applied to the surface and given time to penetrate any cracks. Then the surface is cleaned and a developer is applied which extracts some of the penetrant allowing visual detection of the cracks. Sometimes ultraviolet light is used to enhance detectability.

D.7.3.2 Applications

It is used for the detection of surface cracks and is usually applied on austenitic steel, duplex steel, fully martensitic stainless steel, aluminium or other non-magnetisable construction materials.

D.7.3.3 Inspection results

It is similar to visual inspection, in that only the defect dimensions on the object's surface can be measured such as the length of linear indications. Crack depth cannot be measured. A distinction can be made between linear and non-linear indications. If the surface is too heavily ground, when preparing it for inspection, material can be smeared over the defect causing its concealment. This can be a drawback for the application of penetrant inspection (Note that this is generally not a major problem for Magnetic Particle Inspection).

D.7.4 Radiographic testing (RT)

D.7.4.1 Description

The object is irradiated with X-rays or gamma-rays. The source is placed on one side of the object under inspection and the film on the other side. In this way, an image of the object is produced. A decrease of the irradiated thickness by the presence of a defect results in a higher density of radiation on the film directly underneath the defect. In this way weld defects, cracks, casting cavities and, to a certain extent, geometrical deviations may be detected. In principle, this technique is only suitable for detecting planar defects more or less aligned with the beam, when they can generate sufficient difference in the density of radiation on the film.

Radiography is one of the most commonly used methods for volumetric inspection. The energy of the source to be used depends on the thickness and type of material to be irradiated. An increasing wall thickness results in a decreasing defect detectability. Also an appropriate choice of energy source and type of film greatly influences the detection of defects.

D.7.4.2 Applications

It can be used to detect defects in the volume of specimen as well as surface breaking defects, in welds and castings. RT is well suited for detection of voluminous defects such as cavities and porosity, but also linear defects such as cracks, lack of fusion and incomplete penetration may be detected provided they are quite aligned with the beam of radiation.

D.7.4.3 Inspection results

Radiography is not capable of measuring the through-thickness height of defects with any significant accuracy only the length of a defect can be measured. In addition, radiography is a very powerful tool because it enables the defect to be characterised. The two dimensional picture of the defect gives a direct idea of its shape enabling characterisation.

D.7.4.4 Enhancement of RT

The following possibilities can be considered:

a) The removal of weld reinforcement will improve the contrast when defects are encountered near or in a weld, thereby increasing the probability of detection;

b) If RT is carried out at different angles there will be more chance of detecting and determining the length of a defect;

c) The use of fine grained film will increase the probability of detection;

d) Lower energy X-rays will have a higher resolution than the commonly prescribed high energy isotope sources;

e) Image analysis of the film or video images will increase the probability of detection and improve the determination of length.

D.7.5 Manual ultrasonic techniques using pulse echo signals (UT)

D.7.5.1 Description

Ultrasonic pulse echo inspection relies on the reflection of ultrasonic waves by imperfections in the material under inspection, such as cavities, cracks and weld defects. Pulses of ultrasonic waves are generally emitted and received by piezoelectric probes. Ultrasonic waves can be transmitted perpendicularly into the material (normal incidence), enabling wall thickness measurement or detection of defects with their main dimensions parallel to the scanning surface, see Figure D.3. Ultrasonic waves can also be introduced at an angle, using angle probes placed in the neighbourhood of the weld, to detect weld defects with other orientations e.g. weld defects along the fusion line, see Figure D.4

Pulse echo ultrasonic inspection is a relative method; i.e. results are always related to signals obtained in a known situation (i.e. comparison is made with the signals received from reference reflectors such as holes and notches, a known wall thickness etc.).

The success of the method depends on the probe being accurately placed to receive the mirror-like reflection from the defect. If the orientation of a planar defect is misjudged, then the defect will either not be detected or misinterpreted due to a smaller reflecting signal. Tightly closed planar defects can also be missed when the sound is transmitted through the defect instead of being reflected. This can happen with fatigue crack. The reflections from non-planar defects are weaker than from planar defects but the chance of missing a non-planar defect is much smaller because of the greater chance of receiving a reflection despite a smaller signal. Thus optimised procedures are needed. This means the careful selection of probe angles to transmit and receive signals. The emission of ultrasonic wave pulses by a set of probes with different incident angles will enable insonification (irradiation) of the region where defects are expected. To hit these defects perpendicularly, and to allow the receipt of the reflections from the expected defects, sufficient space on either side of a weld is required.

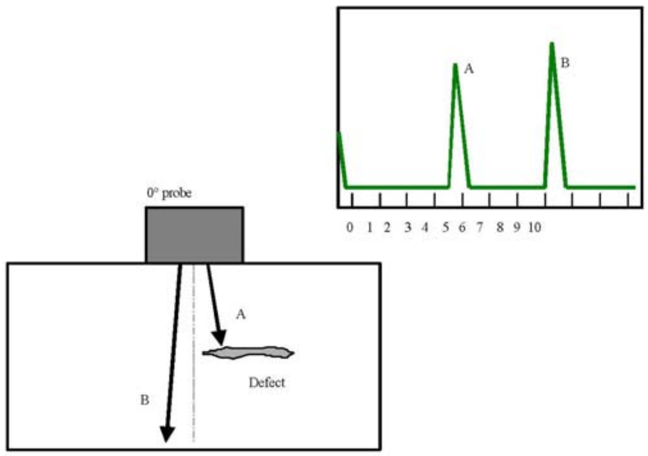


Figure 25 Normal incidence of ultrasonic waves

Figure D.3 – Normal incidence of ultrasonic waves

The portions A and B of the beam from the probe are reflected back to the probe. The peaks A and B give a schematic idea of the response as observed using an oscilloscope. The distance of the peaks from the origin represent for peak A, the depth of the defect and peak B, the thickness of the plate. If the reflector is not specular there will be many additional smaller peaks looking similar to noise caused by the scattered signal. In some cases this can significantly influence the interpretation.

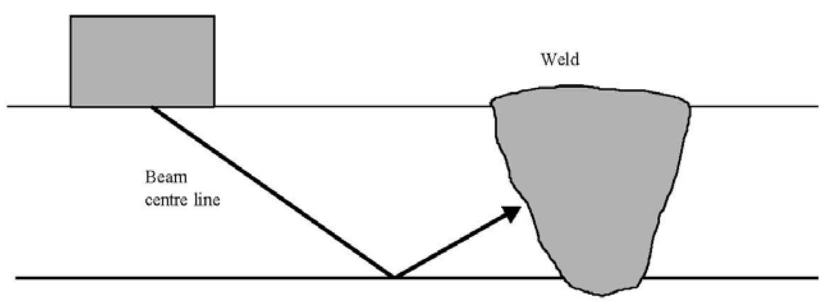


Figure 26 Angle probe for butt weld inspection

Figure D.4 – Angle probe for butt weld inspection

The location of the angle probe and selection of the angle of the probe is critical for the insonification (irradiation) of a defect in the fusion line between the weld and plate and its detection via the reflection of the ultrasonic beam. This means that a minimum distance, dependent on the plate thickness and the probe angle, will be needed between the probe and the weld fusion line for the beam to be reflected and detected at the optimal angles. The beam is not a line but will have a certain diameter depending on the type of probe chosen (e.g. 10 mm for non-focussed probes and 2 to 3 mm for focussed probes). The main reflection peak will be accompanied by a number of sub-peaks. In some cases this can hinder the interpretation. Manual pulse echo ultrasonic inspection, together with radiography, is among the most commonly used methods for volumetric inspection (inspecting the whole volume of material). Normally ultrasonic frequencies between 1 and 10 MHz are used, except in some special applications where much higher frequencies are used to detect and size very small defects. Signals are displayed on an screen and interpreted directly from the screen.

D.7.5.2 Applications

The main applications of manual ultrasonics are weld inspections and wall thickness measurement. UT is extensively used on steel constructions and piping, vessels, tanks and castings. It is applicable to most construction materials, although some materials may be difficult to inspect due to coarse grain structure or anisotropic behaviour, resulting in high “acoustical noise”, damping and beam deflection (e.g. austenitic steel, brass and synthetic materials). Special probes in combination with validated special procedures can often provide a solution in these cases. Specialised UT techniques are available for the detection of surface defects such as small cracks.

D.7.5.3 Inspection results

In an UT inspection any defects that are detected will appear as “peaks” on the screen, which are interpreted by the operator and correlated to possible defects or geometry. The position of the indication on the screen, together with known probe angle and probe position on the material under inspection, provide the operator with information on the location of the defect in the material. Signal amplitude gives a relative measure for defect severity in terms of code requirements, because it is related to the signal of a known reference reflector (e.g. a notch or hole in the material). The signal amplitude does not supply explicit information about the true height of a defect because the signal amplitude depends on more parameters than defect size alone, such as surface condition, defect type, orientation relative to the ultrasonic incident beam etc.

Defect length can be estimated with a reasonable degree of accuracy from the loss of signal as the probe is moved along the length of a defect. The wider the ultrasonic beam diameter the greater the inaccuracy of the measurement of defect length. Also variation in orientation of the defect will lead to inaccuracy or misinterpretation of the defect length. The appearance of the signal on the screen provides the operator with some information about the reflector. Correct interpretation of the signal to determine the defect type depends greatly on the experience and skill of the individual operator, as well as his knowledge, not only of the NDE technique, but also on the welding process, construction details etc. When ultrasonic inspection is used for wall thickness measurement, wall thickness can be derived from the transit time for the ultrasound to travel to the opposite surface of the material under inspection and return to the probe, and the velocity of ultrasound in the material.

D.7.5.4 Enhancement of UT

The following possibilities can be considered:

a) removing or reducing surface roughness and/or the weld cap or root by grinding flush with the plate surface can enhance UT;

b) mechanisation;

c) for vertical defects the use of tandem techniques or TOFD. I.e. so that transmitting and receiver probes are moved in tandem;

d) the use of specially built angled probes that are suited to a particular geometry will increase the Probability Of Detection (POD) and accuracy;

e) rather than just looking at the signal amplitude and transit distance at a given probe position, it can help to record the behaviour of one of them or both during a dynamic scan. Such records are called echo envelope curves, and they can help to reduce the inherent limitations of UT to characterise defects. Another tool, offering more or less similar advantages, is the presentation of digitised ultrasonic images so-called B-Scan, C-scan, D-Scan ….

f) multiple probes or phased arrays can be used to increase the number of angles at which pulses of ultrasound are transmitted into a body. Phased arrays are capable of dynamic swivelling and focusing of the ultrasonic beam. The number of directions that pulses are sent into an object will increase both POD. It goes without saying that specialised software is needed to analyse the received signals in these more complex arrangements. Note that phased arrays can be used for monitoring defects if the direction of defect growth is uncertain.

g) focused probes are used to obtain tip reflections and can be used to increase sensitivity and accuracy. In the hands of an expert NDE inspector this technique can lead to an accurate estimate of defect height or depth.

h) for very thin materials, or in surface layers (up to 1 mm) high frequency probes can be used to detect very small defects such as the initiation of hydrogen cracking. Care should be taken however, because the high frequency probes will be sensitive to a variety of microstructural features which may result in false calls. In very special cases the high frequency probes can be used to detect coarse grained microstructures, which may be suspected as being brittle.

D.7.6 Eddy current technique

D.7.6.1 Description

In eddy current inspection a coil, in which a high radio frequency (RF) current is induced, is brought close to the object under inspection. The material of the object influences the electrical impedance of the coil. Defects are detectable through readily recognisable patterns in the changes of the impedance. Depending on defect type and position, also the phase of the signal is changed. By analysing the phase changes, the effects of lift-off, conductivity, permeability as well as defect type may be separated. Eddy current inspection on magnetisable materials is more difficult than on non-magnetisable materials, because of the reduced penetration depth of the current. Both procedures for application as well as acceptance criteria are laid down in codes and specifications.

D.7.6.2 Applications

The main application is crack detection (at or near the surface) on carbon steel components. On non-magnetisable materials, the main applications are in the aircraft industry and in the inspection of heat exchangers, for corrosion and crack detection, thickness measurement, material characterisation, as well as conductivity and permeability measurements.

D.7.6.3 Inspection results

When applied to detect cracks in carbon steels, the results are semi-quantitative rather than quantitative. Although specialised algorithms for crack depth sizing exist, the accuracy is limited. The results are much more accurate when used to detect corrosion and make wall thickness measurements. On non-magnetisable materials the results can be quantitative. In many cases, defect severity (crack depth, corrosion extent) can be readily measured.

D.7.7 Acoustic emission

D.7.7.1 Description

Acoustic Emission (AE) is a method that is used to detect defects under applied stress. The structure or vessel under test is subjected to a stress (usually slightly greater than previous maximum operating level) by mechanical, pressure or thermal means. Under these conditions, crack growth, local yielding or corrosion product fracture may occur resulting in a sudden release of energy, part of which will be converted to elastic (acoustic) waves. These acoustic waves are readily detected by piezoelectric transducers strategically positioned on the structure. By using methods of triangulation, the detected signals can provide positional information about the emitting defect.

D.7.7.2 Application

AE is often used in conjunction with the initial hydrostatic pressure testing of vessels or piping. AE has also been used to monitor atmospheric storage tanks (without application of additional stress), listening for corrosion product fracture.

D.7.7.3 Inspection results

When compared to a previous test, the amplitude of the received signals can give an indication of the rate of growth of the defect.

AE can be a very sensitive test method and has unique advantages in that:

- It generally surveys the whole structure under test.
- It does not require full access.
- Only registers the presence of 'active' defects.

However, it also has the disadvantage that it is very difficult to justify in comparison with conventional NDE techniques applied with full access. It is vital that there is confidence in the use of AE (resulting from experience of similar applications), particularly as the test is dynamic and cannot easily be verified by repetition. In general, it is not recommended that AE is used as the sole method of inspection unless there is rigour in justification.

D.7.8 Thermography

D.7.8.1 Description

Thermography is a rapid, remote, inspection technique that produces a heat picture of the surface of a component using special cameras (imageries). These are sensitive to the invisible infrared radiation emitted by the component - temperature variations being displayed as different colours. Dependent on the imager, variations in surface temperature as small as 0.1°C can be detected.

D.7.8.2 Applications

Inspection by thermography can detect faults in any component where these result in a change in surface temperature. In addition, because thermography is a passive technique (no stimulation of and no physical contact with the component being required), inspection by thermography is truly remote, allowing the safe inspection/monitoring of components under full plant operating conditions. Inspection of components, during plant operation, is often carried out from as far away as 20m.

Thermography has a wide range of applications; the most relevant important being the inspection of insulated pipework and vessels for potential corrosion under insulation (CUI) sites. Dependent on the temperature of the product contained these sites show up as either 'hot' or 'cold' spots on the heat picture due to the effect of moisture which increases local thermal conductivity. However, in order to be able to detect these hot/cold spots there must be a temperature differential across the thickness of the component of at least 10°C. For some field applications, factors such as changes in surface emissivity, the affects of solar loading (sunlight heating the component) and atmospheric effects may need to be considered.

D.7.8.3 Inspection results

The results are presented as an infra-red images or a video coded in false colors related to the object under inspection.

D.8 Specific NDE for fatigue and weld defects assessment

TOFD can also be used for corrosion and creep assessment

D.8.1 Mechanised ultrasonic technique using pulse-echo signals

D.8.1.1 Description

The principal difference between manual and mechanised pulse-echo technique is that in mechanised pulse-echo UT both the probe position and the ultrasonic signals are continuously measured and recorded, so that the position of detected defects can be exactly reproduced. It is thus possible to generate images of indications (map, cross-sections etc.) as opposed to only a signal amplitude. Often more than one probe is used simultaneously, dividing the wall thickness in a number of zones, each inspected by a separate probe or a mechanised meandering movement is used by one probe to cover the inspection volume.

Various degrees of mechanisation may be used. In most cases the probe (or probes) is moved over the object by aid of a mechanical scanner, but sometimes the probe is manipulated manually (in which case additional equipment is needed to record probe position and orientation). Processing of the results may be accomplished in various ways, ranging from the numerical display of inspection results (for instance wall thickness readings) to the display of fully coherent colour-coded images. With appropriate computer algorithms it is sometimes possible to automate interpretation and let the equipment make decisions on acceptance or rejection, on the basis of pre-programmed criteria. In the latter case one speaks of Automated Ultrasonic Technique (AUT) rather than mechanised.

D.8.1.2 Applications

The range of applications is basically the same as for manual inspection but AUT is now more and more used for pipelines inspection. The reasons for preferring mechanised inspection above manual inspection are:

a) the need for a permanent inspection record;

b) the need for increased reliability;

c) reproducibility (e.g. repetition of in-service inspection);

d) inspection in inaccessible locations (radiation, narrow access, high temperature);

e) inspection of many welds with the same geometry at high speed (cost-effective).

D.8.1.3 Inspection results

Mechanised ultrasonic inspection can, offer more quantitative results than its manual counterpart. This is, on the one hand, due to the fact that it can produce coherent images, showing the amplitude and place of origin of the signals. On the other hand, mechanised ultrasonic inspection allows the possibility of using transducers with sharp focused beams, enabling the inspection of different zones in the material with dedicated transducers. Together with knowledge of the possible defect expected, and using interpretation skills, this can result (to a certain extent) in providing an estimate of the height of any defects present. The defect length can be readily measured as with manual pulse echo ultrasonics.

D.8.2 Time of flight diffraction (TOFD)

D.8.2.1 Description

The TOFD technique relies on the diffracted signals from the edges of defects rather than specular reflections, see Figure D.5. Defects can be detected by transforming these signals into images of the defect, whereby the signal amplitude plays a secondary role. Through-thickness positions and height can be established by measuring the time of flight of the signals, by means of screen observation supported by dedicated software algorithms.

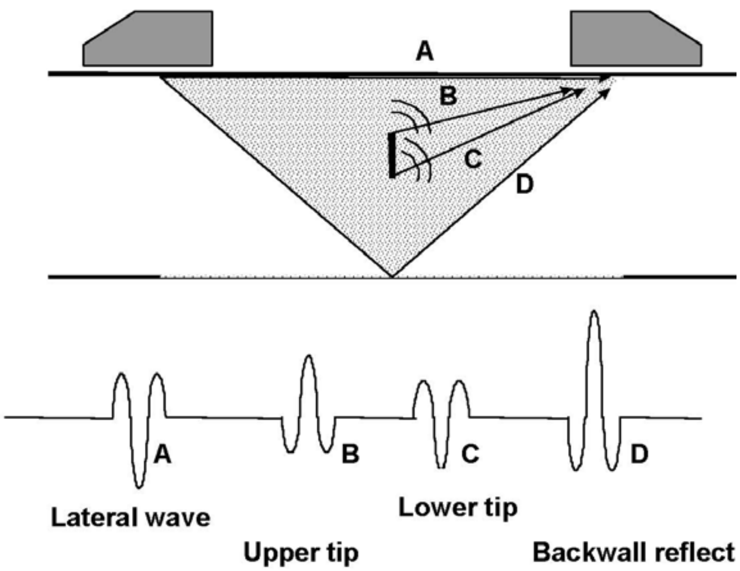


Figure 27 TOFD signals

Figure D.5 – Transmitter receiver

A TOFD inspection is performed with the aid of two probes (transmitter and receiver) which are, in weld inspection, placed on either side of the weld or in another appropriate configuration if the geometry is more complicated. This probe pair is moved along the weld in a single direction. Signals are recorded by means of a computer and a coherent image is displayed on the computer screen, in gradations of a colour (usually grey) scale. From this image, the positions of defect extremities with respect to a reference (e.g. the object surface) may be determined. The probability of detecting a defect, whether it be planar or non-planar is relatively high because a more diffuse diffracted wave is detected. Close to the scanning surface, the TOFD technique has an inherent “dead zone”. However, this dead zone can be minimised by using high-resolution probes and/or by specialised software algorithms. The extent of this dead zone may vary, dependent on the specific application, between a few tenths of a millimetre and some millimetres. In practical applications, a similar “dead zone” can also occur near the opposite surface, caused by geometry (e.g. hi-lo), causing small surface defects to be screened by the back wall reflection.

In practice this means, that sometimes TOFD must be supplemented by additional surface inspection techniques to obtain full coverage. TOFD is usually applied in a (semi-) mechanised way and provides a permanent record of all produced signals.

The use of a transmitter and a receiver probe for weld inspection means that a certain minimum distance on either side of the weld is needed. This is of the order of three times the plate thickness on either side of the weld. A working space of at least 150 mm is needed above the surface on which the probes are placed.

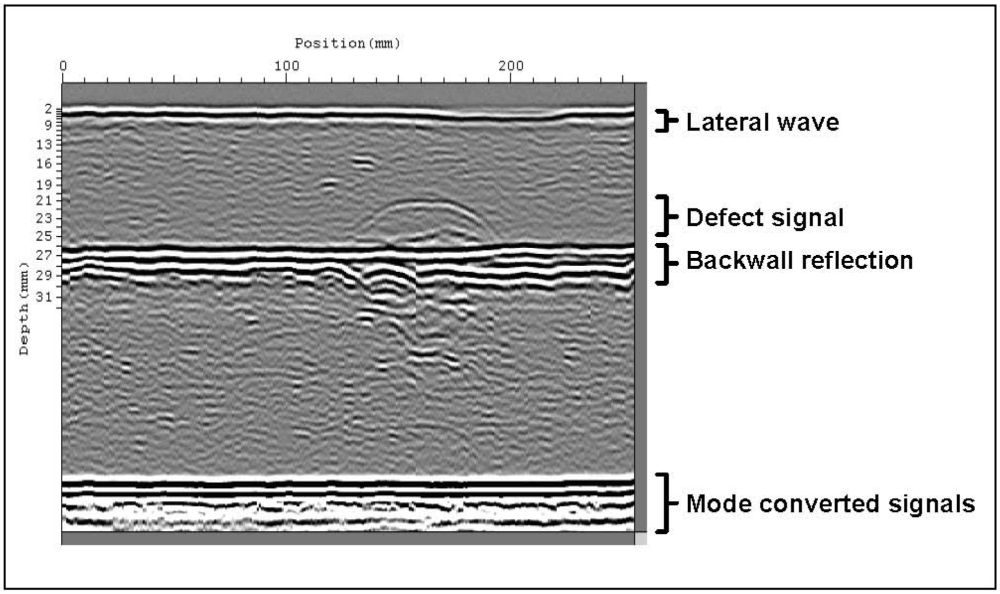


Figure 28 Typical TOFD image

Figure D.6 – Typical TOFD image

Figure D.6 is a typical TOFD image and can be interpreted as follows. The distance from the lateral wave to the semi-circular diffraction pattern of the defect signal represents the distance of the defect to the near surface where the probes are placed. This means that a part of the defect is coincident with the scale that gives 22 mm. Parts of the defect signal indicate that the defect crosses the back-wall reflection. This means that parts of the defect penetrate the wall thickness. The proper shape of the defect cannot be deduced from the figure because the figure represents the transit times of ultrasonic waves and not the physical size of defect. The latter may be obtained by using a transformation algorithm and is performed off-line because of the heavy demand on computing time.

There are in fact two back-wall echoes, namely, the echo of longitudinal waves and the back-wall reflection of transverse waves (mode-converted signals in Figure D.5). The lateral wave travels along the surface and can be used to detect and size near surface defects. Specification for the application of TOFD for weld defects already exist (TS 14751) and national acceptance criteria have already been issued (Kint in Nederland, ASME code Case 2235-2 in USA). European Acceptance Criteria are under development in the frame of the European TOFDPROOF project

D.8.2.2 Applications

TOFD is applied for volumetric inspection, usually in cases where both detection and sizing is required. The same scan is used for both detection and sizing. Other methods usually require different techniques for detection and sizing giving TOFD a potential for being both time and cost efficient. In addition TOFD may be used to size defects initially detected by other techniques. A common application of TOFD is fingerprinting of newly built installations for future reference. The quantitative nature of the results makes the technique very suitable for use in fitness for purpose situations. The defect-sizing capabilities may be used as the basis for fracture mechanics calculations.

D.8.2.3 Inspection results

TOFD inspection results appear in terms of defect position, length, and location in vertical direction and, if defect height is above a certain threshold, also defect height. The threshold for defect height sizing depends on the resolution with which signals from upper and lower tip can be separated, and depends on the ultrasonic frequency (selected on the basis of wall thickness and material properties) and equipment resolution. Typical values for minimum height that can be resolved are 1 to 3 mm.

D.8.2.4 Enhancement of TOFD

The following possibilities can be considered:

a) Increasing the frequency to obtain a higher resolution of defects can enhance TOFD. This is only possible if the material's structure is sufficiently fine and not anisotropic.

b) Specialised software is needed to analyse the signals diffracted by defects near the surface; e.g. software features for linearization, straightening, removal of the lateral wave, detection and sizing techniques, etc.

c) Additional scans can help to better establish defect position and orientation. Normally only a scan is made along the weld (D-scan). To establish higher accuracy and probability of detection, scanning can be carried out across the weld, although this usually requires grinding the weld cap.

d) Because of the flexibility of modern multi-channel computer-based systems for ultrasonic inspection, it may be an advantage to combine ultrasonic techniques such as pulse echo and TOFD inspection. In such a way, full advantage of the merits of both techniques can be taken in terms of defect detection and sizing. With one technique acting as a "safety net" for another, the reliability and quality of the inspection may, in some cases, be enhanced.

D.8.3 Potential drop methods

D.8.3.1 Description

Potential drop techniques are based on the measurement of voltage (potential) along the surface of a metallic conductor (specimen or component) which has an electrical current passing through it. The potential measured depends on the electrical resistance between the measuring points, and this is changed by the introduction or growth of a crack. Thus initiation of cracking and changes in crack length can be monitored by the measured potential.

D.8.3.2 AC-PD System:

Using alternating current means that it is the change in specimen impedance, rather than resistance, which has to be considered. The current is confined to the surface layers of the specimen (the so-called 'skin-effect'), which means that a much low current (approximately 1 A) is required. The sensitivity is greater than with DC methods, and a virtually linear relationship with crack depth is achieved. It is also possible to select the frequency (approximately 460Hz) which is used for different materials. However AC-PD-systems are a far more complex piece of equipment than the DC-PDsystems, thus being more expensive, Additionally AC-PD-systems suffer from inductive pick up which DC- PD-systems do not. This means that great care must be taken in positioning the current input and measurement leads. Connections must be robust, as movement of connections during a test will change the results. Other precautions include twisting together the input and exit leads of each pair of current and potential measurement cables, and minimising the loop area enclosed by both the current and voltage leads, to reduce the magnitude of any inductive pick up. One pair of electrodes is spot welded across the notch. The signal is input into a Lock-In-amplifier via transformer.

D.8.3.3 DC-PD System:

The DC System is identical, except that:

a) no skin effect is operating

b) PD-signals are microvolts so needing strong amplfication

c) No twisting is needed for current and PD wirings

A special version, called reversing DC Electrical PD method was developed, in order to improve accuracy (by using a reference signal to minimize effects due to possible temperature fluctuations) and to eliminate e.m.f. potentials (by periodically reversing the DC current, i.e. using a square waveform for currents and potentials): [2], [3].

D.8.3.4 Applications

These methods can be used for the sizing of surface breaking cracks, which have been previously detected by other techniques.

D.8.3.5 Inspection results

By using the PD four electrical connections are required to be made to the specimens, two current and two voltage. It is important to obtain a good electrical contact between leads and specimen and it is usual to use spot welded, soldered or screwed connections in this respect. The current leads should be positioned such that the current path enclosed the crack. The voltage sensing leads should be positioned symmetrically about the crack site and between the current connections. The inspection result is presented in terms of a measured value for the defect depth. Defect length can be inferred from the measurement positions along the defect where no depth is recorded. Nevertheless, it is more usual to combine the method with a surface method, which is used for detection and the measurement of defect length.

D.8.4 Alternating current field measurement (ACFM) technique:

D.8.4.1 Description

ACFM is an electromagnetic technique used for the detection and sizing of surface flaws in metallic components. The technique does not require any electrical contact with the surface of the component being inspected, and as such, can be used to inspect through coatings of various thickness and material. ACFM works by inducing a uniform electric current (AC) into the component; the presence of any surface flaw disturbs this uniform field, and measurement of the associated magnetic fields parallel to the flaw and perpendicular to the component surface allows flaw detection and sizing using specialist probes, instrumentation and software. In its simplest form, ACFM involves the use of a single hand-held probe, which contains the field induction and the field measurement sensors. The probe is connected to an ACFM instrument, which is computer controlled, providing data display and recording. ACFM is usually deployed manually but can be automated. Probes with multi-element arrays for large area coverage are available as well as probes for high temperature applications.

D.8.4.2 Applications

ACFM can be used to inspect a variety of simple and complex welded components and can be used on a wide range of materials e.g. carbon steels, stainless steels, aluminium. (Note: when used on carbon steel components, ACFM is only suitable for the detection of surface-breaking flaws; while for some non-magnetic materials, a sub-surface capability exists).

D.8.4.3 Inspection results

ACFM provides information on flaw length and depth and can be used through coatings up to 5mm thick. Because flaw detection and sizing is based on the theoretical analysis of the measured signals there is no need for prior calibration.

D.9 Specific NDE for creep assessment (of Plants)

D.9.1 General Considerations

Creep degradation controls most ageing phenomena on components under stress at high temperature. Moreover, detection of creep degradation is a complex problem, requiring advanced technology. Creep strains can be measured using dimensional analysis and results from micrometer or similar instruments. When defects appear, large cracks, small cracks and micro-cracks can be detected using the techniques described elsewhere in this Annex.. However metallographic studies and semi-destructive techniques are needed to determine the real creep degradation status of materials.

Plastic deformation and residual stresses can now be measured with new ultrasonic based and X-ray diffraction techniques. The techniques described below provide information on existing defects which sometimes are related to creep, among others degradation mechanisms.

D.9.2 Destructive Testing

This requires removal of material samples and means that component integrity can be affected, because it is necessary to remove material from the most highly damaged area. The cost of this is prohibitive and a representative sample is needed. However, this is the most rigorous method to determine the amount of creep damage.

D.9.3 Visual Inspection

This technique is often utilized for general inspection. Checks should be made for external defects, such as distortion, bulging and swelling which are indications of excessive creep. Overheating by flame impingement or lack of cooling can also produce visual defectiveness or, possibly, glazing. This technique is not sensitive, is very dependant on inspector experience and will not identify damage in all situations. Nevertheless, it is useful when combined with other methods and is very cheap.

D.9.4 Ultrasonic Attenuation (UT)

Creep attenuates the signal thus ultrasonic attenuation allows for identification of damaged areas. When the surface of the material is rough and the material grain structure is coarse, this makes it difficult to apply normal frequency ultrasonic signals. Different approaches have been applied with different degrees of success.

D.9.5 Eddy Current (ET)

This technique is only used to detect surface defects. The sensitivity of this technique is compromised when the material's permeability changes. Environment and materials affect the evolution of permeability between areas of the components. The technique is often used for tube inspection.

D.9.6 Radiography

Radiographic examination is normally used as a base line and for inspection of some critical areas. Moreover, it is used as a supplementary technique to confirm the presence of severe cases of creep damage. In some cases, in place of X-ray tubes, it is possible to use radio-isotopes. This is the situation for reformer tubes, in which radio-isotopes can be added to the catalyser. In such cases the image obtained has lower resolution, but it can be used in areas where conventional X-ray tubes are not usable. The main limitation of X-ray imaging lies in detection and measurement of crack size. Another limitation lies in the need to ensure the safe use of X-ray and gamma radiation.

D.9.7 Alternating Current Potential Drop (ACPD)

ACPD is used to measure crack dimensions, but is only suitable for an opening crack at the surface [14]. The alternating current is put on the conducting component and a uniform electric field is set up on the component surface with contacting probes. Surface opening cracks disturb the electrical current affecting potential drop across the crack. Measurement of this potential drop allows calculation of the depth of the crack in the unflawed area. Subsurface cracks or some adjacent cracks affect measurement.

D.9.8 Alternating Current Field Measurement

The ACFM technique [15] is an electromagnetic non-contacting technique which has been developed to be able to detect and size surface breaking defects in a range of different materials and through coatings of varying thickness. The basis of the technique is that an alternating current flows in a thin skin near to the surface of any conductor. When a uniform current is introduced into the area under test if the area is defect free the current is undisturbed. If the area were to have a crack present then the current would flow around the ends and the faces of the crack. A magnetic field is present above the surface associated with this uniform current and this will be disturbed if a surface breaking crack is present. These disturbances can be measured and related to the defects that caused them.

D.9.9 Creep Investigation

When creep is suspected, or a location is critical and needs to be inspected for evidence of creep damage or, if a fault is investigated, some actions are usually performed.

- Oxide layer measurement. In steels under high temperature there is growth of an oxide layer, mainly magnetite, in which the thickness is related to steel material, temperature and time of exposure. The thickness of steam-side oxide is usually measured by UT in critical locations and verified with destructive testing in two or three selected locations. Thickness is used to calculate the component temperature within the operational period, taking into account a parabolic change (oxide layer acts as insulating barrier).
- Thermocouples and infrared sensors can be used for on-line operational component temperature. Simulation of material heat transfer behaviour is used for computing real temperature distribution based on actual thermocouple positions. To determine stress level other additional parameters are considered such as internal and external pressures, component geometry, support systems and component weight, erosion and corrosion rates, etc.
- Replicas and hardness results are complemented with temperature and stress information to determine component status by creep degradation.

D.9.10 Creep Before Crack

Before a creep defect is suspected and in addition to conventional techniques to detect incipient defects and cracks, as commented in D.9.1, it is necessary to perform regular inspections for material properties measurement and Creep damage evaluation. The European Creep Collaborative Committee has published some recommendations documents, reviewing Creep detection and evaluation techniques as well as some articles and Conference papers with this objective. The most frequently used techniques, jointly with other promising techniques are described below:

D.9.11 Hardness

The indentation hardness by means of portable hardness tests during in service inspection is frequently used in most materials, especially in metallic materials. In this way, hardness measurements are used to determine the components creep degradation. Usually, hardness measures are performed in the surfaces prepared for replication. The reason is that hardness technique is very cheap, but has some surface preparation requirements.

Hardness is associated with the resistance to movement of dislocations in the materials, i.e. in ferritic steels, and could be correlated with the material creep strength, but it is necessary to take into account that there are high variety of effects affecting hardness, other than creep, including local structural variation and surface condition. In addition, hardness measurement is a surface test, it does not provide information of the overall wall thickness status, and could be dependent on material thickness (10 mm or above to be valid) and measurement orientation. For these reasons, hardness is combined with other techniques, and rarely used alone.

There are some different hardness scales and sometimes it is necessary to modify obtained values to obtain a repetitive and/or compare with reference values. It exist standard conversion tables, which could be used, taking into account that scales are material related.

As conclusion, it is difficulty, and sometimes impossible, to evaluate creep damage considering only hardness values. In addition, hardness is a good tool to help in creep damage interpretation if it is combined with other techniques such as metallographic replicas, X-ray diffraction, etc. The information that this technique provides, includes:

- Indirect information on degradation status of precipitates
- Creep strength differences
- Temperature estimation
- Remaining lifetime prediction and failure location on welds.

At present, computed precise microhardness measurement devices are available. During the test, the relative position indenter to surface is monitored determining the depth of the indent. The system provides hardness directly, without optical of indented area. Additionally, load/displacement curve gives the Young's modulus. These indenters could also provide information on coating adhesion.

D.9.12 Metallographic Replicas

Today, this is the most popular NDT method to determine microstructural degradation and creep strength reduction and cavitations in low alloy steels. Extraction replicas could be obtained from samples removed from components, but usually, the expression is related with surface replicas, consisting in obtain a “photocopy” of the material surface over a cellulose acetate film. The material surface needs to be adequately prepared with a grinding and polishing process. After this process surface is etching and cleaning with a solvent. Applying an acetone deluge and laying on the cellulose acetate film, it is possible to obtain a negative of the surface, which is analysed using optical microscopy, using a high resolution field emission scanning microscope (SEM - scanning electron metallography), transmission electron microscope (TEM), etc.

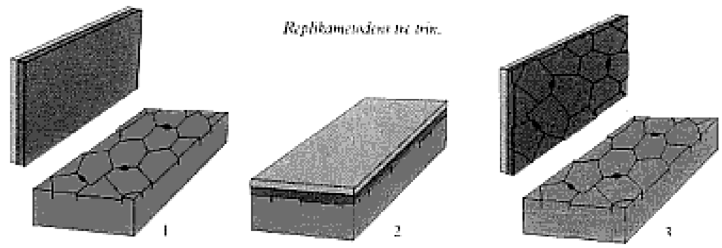


Figure D.7- The replica method as principle (from [11])

In general, replicas are used to study the microstructure: creep cavitation, grain size, and to determine graphite and eta-phase contents and interparticle space. As replica is a surface technique, requires taking into account operational temperature and stresses distribution, look for the most affected area of the compo

Interpretation of this technique results provides valuable information for:

- Determine the state of degradation
- Damage location and classification.
- Remaining lifetime prediction (A parameter and Cavity density)

Estimation of degradation and damage based on surface replicas for low alloy is frequently performed based on Neubauer classification. Unfortunately, information on degradation status for medium and high alloys based on replicas is not well known or impossible to determine.

Neubauer classifications based on creep cavitations, is shown in the attached table (Table 19):

Table 19.- Replica Evaluation. Neubauer classification [19].

Damage class	Description	Comments
A	Undamaged	No creep damage detected. Some evidence of thermal degradation may be seen
B	Isolated	Isolated cavities are observed. It is not possible to deduce the direction of maximum principal stress from the damage seen.
C	Oriented	Cavities are observed, often with multiple cavities on the same boundary. A clear alignment of damage boundaries can be seen, indicating the axis of maximum principal stress.
D	Microcracked	Cavities are observed on boundaries normal to the maximum principal stress. Some boundaries have separated due to the interlinkage of cavities on them to form microcracks. Typically less than 2 mm. May be detected by conventional NDE.
E	Macrocracked	In addition to cavities and microcracks being observed, microcracks have joined together and widened to form macrocracks many grains boundaries long. Typically more than 2 mm, should be detectable by conventional NDE.

The different damage could be represented in the creep evolution curve is shown in Figure D.8. Based on Neubauer classification different standards have introduced modifications to facilitate the application. The most used in Europe are included in the Table 20 [19].

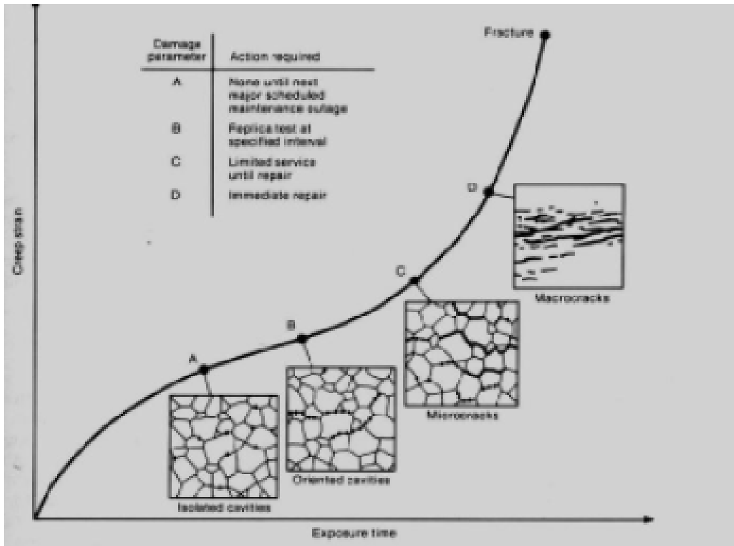


Figure D.8.- Evolution of replicas compared with creep

Table 20.- Replica Evaluation (Different damage scales)

<table>
<tr><th>Damage scale</th><th>No damage</th><th>No cavitation</th><th colspan="3">Isolated cavitation</th><th colspan="4">Oriented cavitation</th><th colspan="3">Microcracks</th><th>Macrocracks</th></tr>
<tr><td>Neubauer</td><td colspan="2">A</td><td colspan="3">B</td><td colspan="4">C</td><td colspan="3">D</td><td>E</td></tr>
<tr><td>NT TR 170</td><td>0</td><td>1</td><td>2.1</td><td>2.2</td><td>2.3</td><td>3.1</td><td colspan="2">3.2</td><td>3.3</td><td>4.1</td><td>4.2</td><td>4.3</td><td>5</td></tr>
<tr><td>VGB-TW507</td><td>0</td><td>1</td><td>2a</td><td colspan="2">2b</td><td colspan="2">3a</td><td colspan="2">3b</td><td colspan="3">2</td><td>5</td></tr>
<tr><td>ISQ</td><td colspan="2">0</td><td>0/1</td><td colspan="2">1</td><td colspan="2">1/2</td><td colspan="2">2</td><td>2/3</td><td>3</td><td>3/4</td><td>4</td></tr>
</table>

D.9.13 Ultrasound

Ultrasonic testing has already become an important NDT technology up to now, which can be used to inspect and judge a lot of welded structures in-service such as off-shore structures, nuclear industries, pressure vessels industries and so on. During last few decades, UT technology has been developed from a purely manual operation technique to a manual operation with computer-aided, even to use automatic scanners [14]. Some laboratory experiences have demonstrated the feasibility of ultrasonic measurements for material properties determination and characterisation, including creep damage specially:

- The precipitates on grain boundaries affect the transmission of the sound, reducing the transmission and causing waves backscattering. Measurements of attenuation and backscatter amplitude have been done in laboratory. Further development could finalise to provide an on-site applicable technique for detection and quantification of precipitates.

- Some works demonstrate that sound velocity could be correlated with precipitates, sigma phase and other thermal ageing related effects.
- Other promising techniques related with spectral analysis and noise relaxation could be applicable in the future. More laboratory work is needed to obtain correlations, to determine materials in which these techniques could be applied and to solve some problems related with on-site application of laboratory issues.

Annular phased array UT has been shown to be effective in the detection of incipient creep cavity development prior the onset of microcracking [23]. Ultrasonic measurement of stress has also performed over plates and sheets. Usually, acoustoelastic constants or other nonlinear properties of the material are needed for stress prediction, but some approaches using EMAT transducer have suppressed these requirements.

D.9.14 Eddy Current

By monitoring changes in circuit impedance , it can be inferred that creep damage is present, based on observation of the signal parameters in comparison to similar changes that occurred on known creep-damaged materials. The depth of penetration of eddy currents is primarily influenced by frequency, conductivity, and relative permeability [10]. Few experiences have been reported in the field of properties measurements using ET techniques. Some effort to detect changes in structure of materials caused by mechanical effort and some researches are considering ET could be a potential technique to detect thermal ageing and creep.

D.9.15 Small scale tests

These techniques are considered as NDT if material removed to do the test is reduced and the extraction technique does not affect the component integrity as well as does not suppose any change in the metallographic structure of the extracted material, avoiding high temperature damage or alteration of the material, modification of the stresses distribution in the component, etc.

Different techniques are available to obtain samples and create the miniature specimens are available. The selection of such extraction technique is dependent on component geometry, accessibility, repairing feasibility (i.e. welding), required number of specimens, etc. The small scale tests available today are [18]:

- Miniature specimen creep test. It is a scale version of the conventional creep tests. Geometry and load distribution are similar to the used in creep tests, and creep rates could be assimilated to those obtained with specimens with standardised dimensions.
- Impression creep test. The indentation creep test performed with flat ended cylindrical punch was originally proposed by Yu and Li in the 70s for investigation of creep properties of materials. Using this method for the investigation of high temperature plasticity of single crystals they have proved that its results are equivalent to those of the tensile creep test. [20].

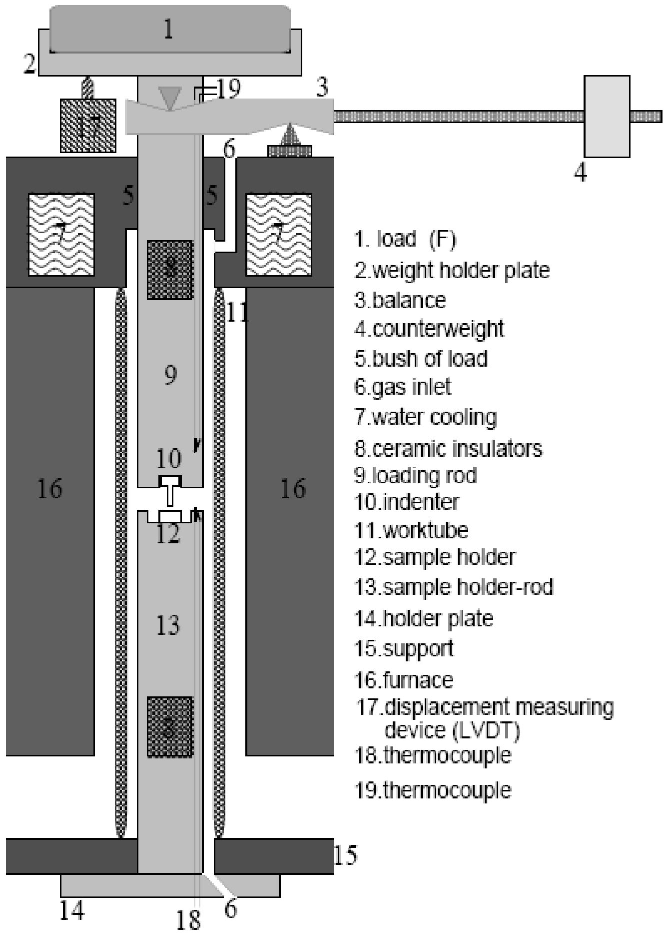


Figure D.9.- High temperature creep indenter scheme [20]

Technique consists in extracting microsamples of the component to be analysed. The samples are used for producing specimens with specific dimensions. The specimens are indented applying a steady load at determined high temperature. The main advantages of this technique are related with the minimal sample preparation required, the high testing speed and minimal microstructural aging during test. It has been suggested that better results can be obtained by performing a series of tests over a creep strain range in which the indentation strain rate in any one test is held constant.

- Small punch test. The small-punch creep test is used to acquire high-temperature creep data from small-scale disk-shaped test specimens.

  The test consists in deforming a supported thin disk-shaped specimen with a spherical penetrator. Tests are performed at a constant load, frequently using dead weights, under a protective environment, typically Argon, and in a constant elevated temperature.

In all creep tests, the selection of samples is a very important issue. It is necessary to take into account the welds, HAZ and singularities to manufacture the adequate specimen in function of test type, component geometry, weld orientation, material properties, etc. The European Creep Collaborative Committee [25] maintain updated the information on creep testing procedures, assessment and sampling methodology, regarding test representatively and uncertainties.

D.9.16 X-ray diffraction

X-Ray Diffraction is a common NDT technique that can be used to determine the levels of residual stress in the near surface layers of a component. X-rays probe a very thin surface layer of the material (typically tens of microns), and it is from this layer that the near surface residual stress is measured. During years, this technique has been restricted to laboratories, as considered as a semidestructive test. For stress detection, the sample needs to be polycrystalline materials.

Following the global area detector for diffraction pattern, it is possible to obtain and automatically

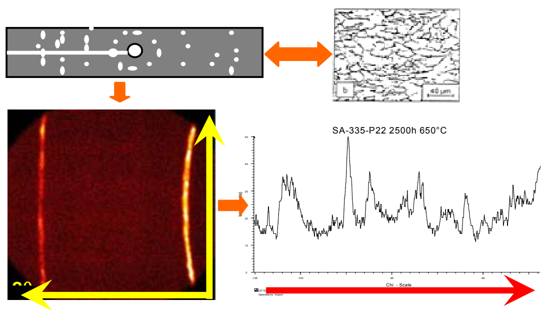


Figure D.10.- Diffraction registers relation

analyse the result. At present, it is possible to correlate the degradation status of the material with the 2D diffraction pattern, determining creep lifetime consumption as well as operating temperature [21].

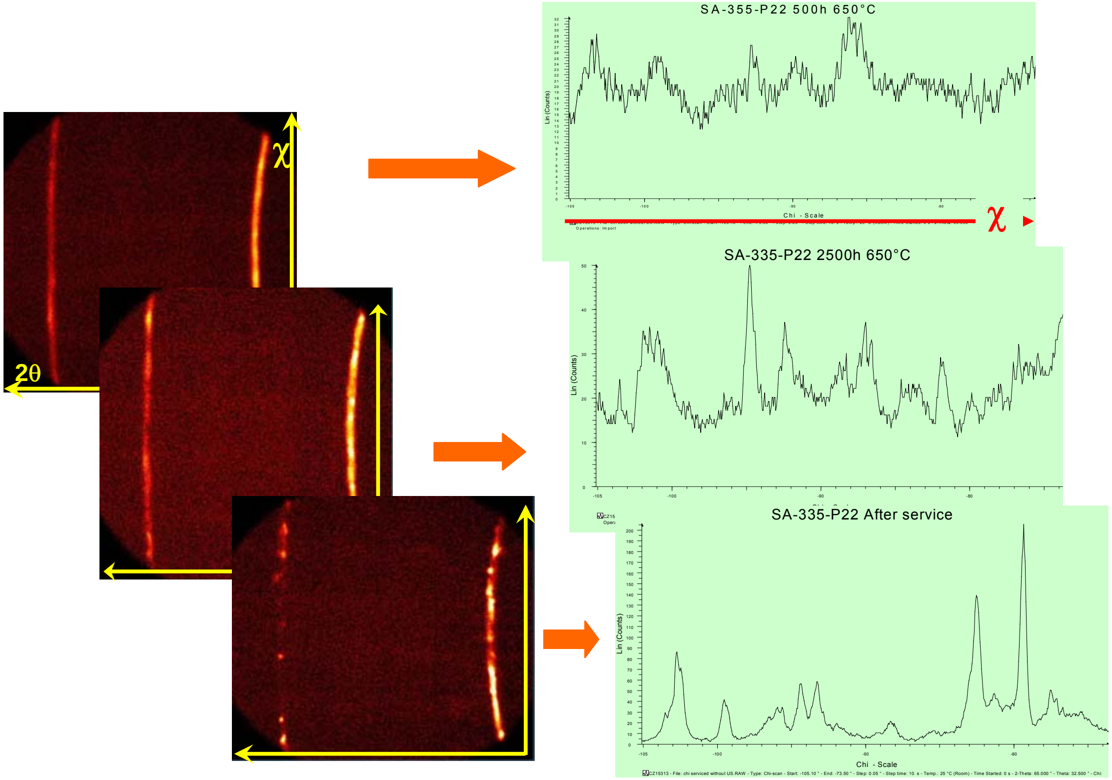


Figure 11.- Diffraction pattern evolution with time.

The Figure 11 shows the evolution with ageing of the diffraction pattern from 500 h to after service operation of P22 steel from a fossil power plant. At present accessible areas for sensors and X-ray sources are limited and number of materials with available data is reduced, only some ferritic steels and very few austenitic steels has been tested.

D.9.17 Laser profilometry

Laser Profilometry is a non-contact, non-destructive inspection technique which utilizes a low-powered laser to profile the surface of an object. [8]. Laser Profilometry technique is used mainly in the internal side of tubes for deformation measurement. Laser Profilometry measures creep strain as a direct result of material expansion, with accuracies of ± 0.005%. It is able to identify and quantify creep damage well before isolated and oriented voids began to appear. Areas of the tube where I.D. expansion or creep damage is evident can be quickly identified and classified according to their percentage of expansion.

D.9.18 Wall thickness measurement

As creep damage occurs, an apparent decrease in wall thickness is usually evident. Average wall thickness measurements during consecutive inspection period could be correlated with the metallographic condition [10]. This technique is used in combination with other, such as roundness (oval) measurement of tubes.

D.9.19 AC magnetic hysteresis

Creep damage and post welding heat treatment temperature were evaluated by AC magnetic hysteresis measurement on some metal, such as Cr-Mo steel and welding metal [16]. Recent studies demonstrate that parameters measured by magnetic method such as coercivity, remanence and hysteresis loss are sensitive to the creep damage. And also the harmonic analysis method of the detected voltage is effective to evaluate the micro structure change of carbon steel. Some on-going projects combine several micro-magnetic testing for characterisation of mechanical properties [24], including such characterising thermal ageing and creep.

D.9.20 Holographic Moire [17]

The permanent deformations associated with the secondary stage of the creep effect must be measured with high sensitivity, in the order of tens of µstrains, and over long time intervals, typically during the periodical maintenance shut-down [17]. The high sensitivity is obtained by using the in-plane holographic moire' technique as the operating principle. The instruments are composed of two optical heads. A writing head, fed by a He-Cd laser through an optical fibre, generates on the surface of the component a reference grating in photo-resist. This is used as a mask for the electroforming of a nickel permanent grating intended to endure temperature and corrosion during the life of the component.

A reading optical head is used to perform the periodical comparison between the same reference grating, provided by the reading head itself, and the deformed grating electroformed on the component. Both heads have an identical isostatic base for precise repositioning by means of three reference spheres soldered to the component. Any difference between the pitch of the grating on the component and the reference grating from the reading head will generate moire fringes with a spacing = p/, where p is the spacing of the reference grating. The sensitivity of the system is in the range of 60 - 5000 µstrain when using a grating spacing of 2.5 µm. Moire fringes are imaged by a CCD

D.9.21 References

[1] Don Searle, Detection and measurement of Reformer Tube Creep. 10th APCDNT Brisbane, 2001.

[2] Richard D. Roberts, John Brightling. All Inclusive Approach for Steam Reformers Inspection Methods, NDTNET Vol 10. No 3. Mar 2005

[3] Eyckmans Marc et al. Evaluating the condition & remaining life of older power plants. 15th WCNDT, Rome, 2000

[4] Rafael Martinez-Oña; Carmen Perez, Research on Creep damage Detection in reformer tubes by Ultrasonic testing. 15th WCNDT, Rome, 2000

[5] Ines and Predrag Dukic, Advantages and Limitations of TOFD Technique in Casting Inspection. 15th WCNDT, Rome, 2000

[6] P. Auerkari, K. Borggreen, J. Storesund, Evaluation of Replica Inspection Results from Power Plants.7th ECNDT Copenhagen, 1998

[7] A. Scheerder Experiences at DSM with NDT and Evaluation of Creep Damages in Reformer Tubes. 7th ECNDT Copenhagen, 1998

[8] Richard D. Roberts, Advancements In Laser Profilometry Applied To Reformer Tubes For Detection Of Creep Damage Provides A Step Change In Steam Methane Reformer (SMR) Management. NDTNET Vol 8. No 9. Sept 2003

[9] ECCC Recommendations 2003, Publ. European Technology Development Ltd, Ashtead

[10] Brian Shannon, Carl Jaspe, A Comprehensive Approach to Reformer Tube Inspection and Assessment, 2nd MENDT, Jubail Industrial City, Saudi Arabia, 2003

[11] J. Vagn Hansen.Non-Destructive Metallography Used On-Site, Possibilites and Experiences. 7th ECNDT Copenhagen, 1998

[12] S R Holdsworth, G Merckling, ECCC Developments in the Assessment of Creep-Rupture Properties, Parsons Conference, Dublin, Sept 2003

[13] N. Raghu et al. In-situ Metallography for Damage Assessment and Life Extension in Power Plant - A Few Case Studies. WCNDT '96 - New Delhi

[14] Chen Guo-hua, The Advancement of NDT Technology and its Application in the Safety Assessment of Pressure Vessels. . 10th APCDNT Brisbane, 2001.

[15] Alan Raine, The Development of Alternating Current Field Measurement (ACFM) Technology as a Technique for the Detection of Surface Breaking Defects in Conducting Mat. and its Use in Commercial and Industrial Applications, 15th WCNDT, Rome, 2000

[16] M. Shiwa et al., Evaluation of Creep Damage and PWHT Temperature of Low Alloy Steel Using AC Magnetic Method. EPRI 2nd Int. Conf. on NDE in Relation to Structural Integrity for Nuclear and Pressurized Components, New Orleans, 2000

[17] L.M. Rizzi et al., Creep Monitoring in Power Plants by a Holographic Moire System. 7th ECNDT Copenhagen, 1998

[18] S J Brett, G Merckling, Comparative Applicability Evaluation of Specific Testing Techniques for Post Exposure Material Creep Behaviour Investigation, High Temperature Plant Integrity & Life Extension Conference, Cambridge, April 2004

[19] A.S.Jovanovich, Project Advanced Life Assessment System (ALIAS) presentation. Replica Evaluation.

[20] Géza Cseh, Indentation Creep for the Investigation of High Temperature Plastic Behaviour, PhD dissertation. Eötvös Loránd University, 2000

[21] V.Kolarik et al. Xpection – Material assessment in industrial high temperature plants using real structure analysis by on site X-ray diffraction. High Temperature Plant Integrity and Life Extension Conference. Cambridge, 2005

[22] I. Marcelles et al. Remaining Life Evaluation of High Temperature Components by X-ray Diffraction. ECCC Conference. London, 2005

[23] L. Bisbee. Enhanced Methodologies used for the Assessment of High Temperature Reader Girth Welds. International Conference Welds, Hamburg, GKSS, 2005

[24] G. Dobmann, I. Altpeter, K. Szielasko, non-Destructive Characterisation of Thermal Ageing of the Cu-rich WB36 Steel 15 NiCuMoNb5 (1.6368). Int. Con Welds, GKSS, Hamburg, 2005

[25] http://www.etd1.co.uk/**eccc**/advanced**creep/**

D.10 Specific NDE for corrosion assessment

D.10.1 Magnetic flux leakage (MFL)

D.10.1.1 Description

The magnetic flux leakage or MFL method uses a strong magnetic field, which saturates the steel wall. Anomalies such as metal losses will locally force field lines to leave the material, thus causing flux leakage that can be detected by means of suitable sensors such as Hall sensors. This approach is suitable for wall thickness up to e.g. 12 mm. In practical applications an array of sensors is used, providing full coverage over an extended surface while scanning.

Since the flux leakage signals are, to a certain extent, dependent of the shape of the corroded spot, the amplitude of the signal does not have a defined relationship to the depth or severity of the corrosion. Although modern algorithms have significantly improved this, an accurate estimation of the remaining wall thickness cannot be given. Therefore these techniques are often used as screening techniques to define suspect areas for further inspection with e.g. ultrasonic wall thickness measurement.

Recently a low frequency eddy current technique was developed for the inspection of thicker walls, up to e.g. 35 mm. This also uses magnetic saturation of the steel wall.

D.10.1.2 Applications

MFL techniques have been used in so called intelligent pigs for on-line inspection of long-distance pipelines, to detect corrosion. In more recent years, the technique is used for the detection of corrosion in flat plates such as storage tank floors, whereby magnet and sensors are integrated in dedicated motor-driven scanner that also houses the electronics. Also special (smaller) scanners for the inspection of pipes and vessel wall exist. Although some applications are known, the MFL method is less suitable for the detection of cracks. The low frequency eddy current variant however is suitable to detect cracking.

D.10.1.3 Inspection results

In the simplest approach, the signals of the sensors can be used to trigger visual or audible alarms, warning the operator that a suspect area has been found. Signals can also be used to generate coherent pictures using a computer, whereby corrosion severity is indicated by colours.

D.10.1.4 Enhancement

MFL can be applied using Superconducting Quantum Interference Devices (SQUID) as sensors, resulting in enhanced sensitivity and resolution.

D.10.2 Long range or multiskips ultrasonic testing methods

So called long range or multiskips ultrasonic methods have been developed to detect corrosion pits in areas that are inaccessible for most techniques. Conventional ultrasonic methods for the inspection of large areas, such as vessels or long pipelines are generally time-consuming and costly. In addition, inaccessible regions such as pipe on supports or under clamps generally cannot be inspected unless the entire assembly is dismantled often involving expensive shutdowns and significant effort and cost. This method can be used for the screening of pipe and plate including vessels, tanks etc. and are suitable for an inaccessible geometry such as inspection under clamps, saddles and pipe supports. They are not capable of indicating remaining wall thickness, but are able to indicate defect severity. If defect areas are found, they are inspected in more detail off-stream with quantitative methods for wall thickness measurement such as UT or MFL. This is also mentioned in Section 8.5 on the selection of combinations of methods.

Examples of these techniques are the LORUS method (Long Range UltraSonics) and multiskips technique, which are based upon the reflections of defects in fully insonified (irradiated) plates, and CHIME (Creeping Headwave Inspection MEthod). These methods are used to detect defects rather than size them. They therefore require the additional use of a quantitative method to size the defects.

LORUS method and multiskips techniques use bulk waves, generated by an angle probe as shown left in Figure D.12. The ultrasonic beam fills the steel component, is able to pass e.g. welded-on obstacles and is reflected by corroded areas. Signals are recorded in coherent colour-coded images indicating the location and extent of the damaged area. The typical range of these techniques is up to 1 metre. The example in the figure is the inspection of a storage tank bottom plate for corrosion. The LORUS probe is positioned on the tank bottom plate which extends beyond the tank wall. This enables the tank to be inspected without the need to empty the tank in the first instance. If significant corrosion is found the tank is emptied and the bottom cleaned so that a quantitative method can be used to measure the loss of wall thickness.

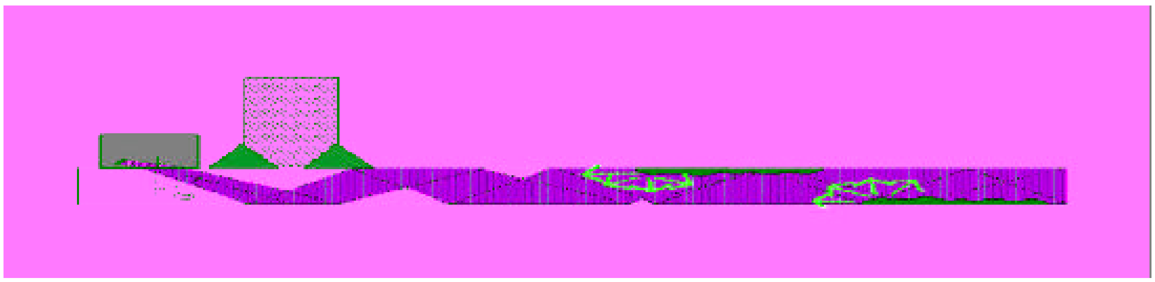


Figure D.12 – Principle of the Multiskips and LORUS® techniques

Chime is a medium range ultrasonic screening technique which provides full volume coverage between the transmitting and receiving probes which can be separated by up to 1m. Figure D. shows a sketch of the experimental set-up on a plate and the resulting A-scan signal from good material. Defects or corrosion between the two ultrasonic probes will affect the signal pattern enabling an indication of defect severity to be given.

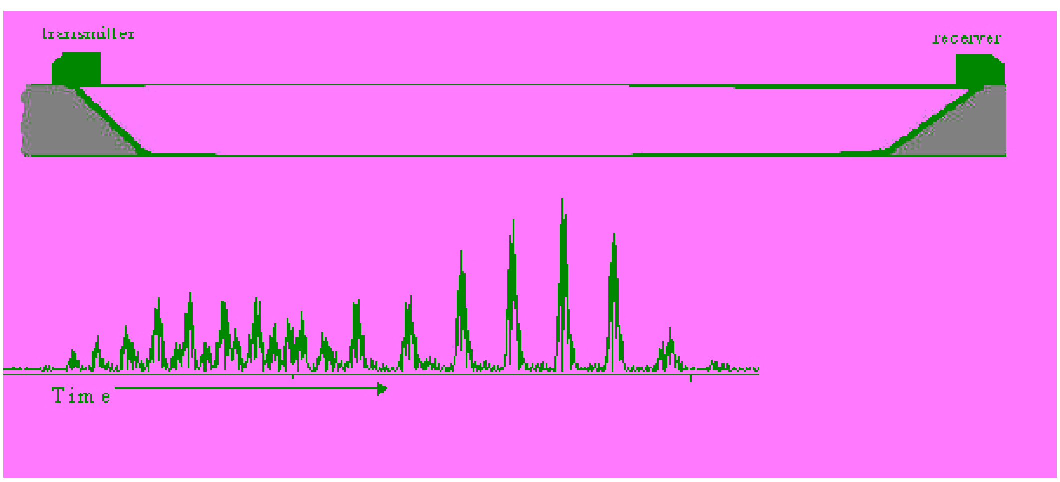


Figure D.13 – Principle of the CHIME technique

D.10.3 Guided waves

D.10.3.1 Description

Two equipments are used in Europe: TELETEST (Plant Integrity Ltd.), WAVEMAKER (Guided Ultrasonics Ltd.). These systems are intended for inspection of long lengths of pipe and utilise low frequency, guided, ultrasonic waves to carry out a 100% volumetric inspection. A single point of access to the pipe surface is all that is required to attach the encircling transducer unit. Liquid couplants are not required, the transducer unit relies on clamping pressure. Ultrasound can be transmitted in one or both directions along the pipe and is reflected by sudden changes in wall thickness due to the presence of flaws. These techniques are most sensitive to an overall reduction in the pipe cross-sectional area.

D.10.3.2 Application

Guided wave techniques are particularly applicable to the detection of corrosion on internal or external pipe surfaces in situations where access is restricted, for example, due to the presence of thermal insulation. A limitation is that the maximum operating range varies according to pipe geometry, contents, coatings/insulation and general condition. In particular, the presence of sound absorbing coatings or material in contact with the pipe can greatly reduce the operating range.

D.10.3.3 Inspection results

Inspection results are presented in terms of a combined A-Scan from the different elements of the encircling transducer. The amplitude of the indication related to a reference curve is assessed, but the remaining thickness cannot be measured (work are in progress to overcome this drawback), neither the side where the corrosion happened (inside or outside the pipe)

D.10.4 Pulsed eddy current technique

D.10.4.1 Description

Pulses instead of a harmonic function excite the coil. The material response is measured with a receiver coil. Information on the material for a large range of wall thickness can be obtained by analysis of the response of the signal. As with other eddy current techniques the measurements are influenced by material properties such as conductivity and permeability. The reference measurement is carried out on a representative, undamaged part of the component.

D.10.4.2 Application

Pulsed eddy current is applied for wall thickness measurements of mainly carbon steels and can be used without the need to remove insulation or coatings and when surfaces are rough. Maximum wall thickness is typically approximately 40 mm. Maximum lift-off (distance between the probe and the surface) or coating thickness can be in the order of up to 200 mm,

e.g. the wall thickness of pipelines, of up to approximately 200 mm, tanks and vessels can be measured with high accuracy, with a significant lift-off. This enables detection of corrosion under insulation. The system can cope with steel and aluminium jackets that contain the insulation and may be used on-stream. It is not suitable for the detection of local (pitting) corrosion. inspection results Inspection results are presented in terms of an absolute value in mm or inches, or a percentage of nominal wall thickness. Procedures for the application and acceptance criteria are under development.

D.11 Bibliography

[D.1] Guidelines for establishing fitness for Purpose of welded constructions. TNO report O1F-01136/KRO-March 2001 – P.Bristoll

[D.2] Best Practice for risk based inspection as a part of plant integrity management : HSE report 363/2001 prepared by TWI and Royal & SunAlliance engineering

[D.3] Catlin, W.R., Lord, D.C., Prater, T.A., and Coffin, L.F.: "The reversing D-C Electrical Potential Method", in Automated Test Methods for Fracture and Fatigue Crack Growth, ASTM STP 877, W.H. Cullen, R.W. Landraf, L.R. Kaisand, and J.H. Underwood Eds., ASTM Philadelphia. 1985, pp.67-85.

[D.4] Bicego, V. Liviero, D. Fossati, C. and Lucon, E. J-R curve testing Utilizing the Reversing Direct Current Electrical PD Method, ASTM STP 1092, Philadelphia, 1990, pp143-166.