FOREWORD

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- **Offshore Service Specifications.** Provide principles and procedures of DNV classification, certification, verification and consultancy services.
- **Offshore Standards.** Provide technical provisions and acceptance criteria for general use by the offshore industry as well as the technical basis for DNV offshore services.
- **Recommended Practices.** Provide proven technology and sound engineering practice as well as guidance for the higher level Offshore Service Specifications and Offshore Standards.

DNV Offshore Codes are offered within the following areas:
A) Qualification, Quality and Safety Methodology
B) Materials Technology
C) Structures
D) Systems
E) Special Facilities
F) Pipelines and Risers
G) Asset Operation
H) Marine Operations
J) Wind Turbines

**Amendments and Corrections**

This document is valid until superseded by a new revision. Minor amendments and corrections will be published in a separate document normally updated twice per year (April and October).

For a complete listing of the changes, see the “Amendments and Corrections” document located at: http://webshop.dnv.com/global/, under category “Offshore Codes”.

The electronic web-versions of the DNV Offshore Codes will be regularly updated to include these amendments and corrections.
Executive summary

Pressure vessels and pressure systems are required to undergo periodic, statutory inspection to ensure continued safe and reliable operation. Traditionally this has been achieved by means of an internal visual inspection (IVI), however, there can be very high costs associated with shutting down a vessel (loss of production), isolating it and preparing it for entry. Indeed, these costs can be much higher than the cost of the inspection itself. Furthermore, the mechanical disturbances involved in preparing the vessel for internal inspection and reinstating it may adversely affect its future performance. Finally, and by no means least, man access may also be hazardous. There can, therefore, be significant advantages if inspections are performed from the outside of the vessel without breaking containment i.e. non-invasively. However, there needs to be a balance between achieving these benefits and obtaining the information required to ensure continued safe and reliable operation.

While it may often be the preferred option, non-intrusive inspection (NII) represents a relatively new approach by comparison to IVI and many engineers responsible for inspection planning have yet to build up experience with and confidence in its application. In addition, there are a wide variety of techniques available, each with its own specific capabilities and limitations.

This has been recognised by industry and has led to the development of a number of guidance documents aimed at assisting plant operators to plan and justify NII. This recommended practice is intended to bring these documents together under a single cover, and to provide a consistent and logical approach at all stages of the non-intrusive inspection process.

This recommended practice is primarily intended for those with responsibilities in the planning, implementation and acceptance of vessel inspections. It is aimed at the inspection of welded vessels constructed from metals, and related items, fittings and connections associated with them, although the document is equally applicable to forged/spun metal pressure vessels, which contain no welds, as well as storage tanks and large diameter pipelines. Although not intended to be covered by this document, some aspects of this recommended practice may also be applicable to vessels manufactured from other materials and plant items other than pressurised equipment, in which case some of the general principles developed may well still apply.

The recommended practice provides guidance for:

i) determining when NII is appropriate in principle
ii) information requirements to plan for NII
iii) defining the requirements for the NII method(s) to be selected
iv) selecting methods that meet the requirements
v) evaluating the results of the inspection
vi) documentation requirements.

Acknowledgements

This recommended practice is based on a number of preceding documents and as such the permission of the previous authors to incorporate their work is hereby gratefully acknowledged. In particular, we would like to thank members of the HOIS collaborative project for their contributions and comments during the production of the recommended practice, Mitsui Babcock for their permission to incorporate elements of the GSP235 report covering aspects of the inspection planning procedure and summary of inspection methods, and ESR Technology Ltd for compiling the original text for this recommended practice.
1. Introduction

1.1 Background

Pressure vessels and pressure systems are required to undergo periodic, statutory and other non-destructive testing to ensure continued safe and reliable operation. This generally includes a requirement to inspect vessels for possible internal degradation. This is frequently achieved by means of an internal visual inspection (IVI) coupled with the use of surface flaw detection methods such as dye penetrant inspection (DPI) and magnetic particle inspection (MPI), however, there can be very high costs associated with shutting down a vessel (loss of production), isolating it and preparing for it for entry. Indeed, these costs can be much higher than the cost of the inspection itself. Furthermore, the mechanical disturbances involved in preparing the vessel for internal inspection and reinstating it may adversely affect its future performance. Finally, and by no means least, man access may also be hazardous.

There can, therefore, be significant advantages if inspections are performed from the outside of the vessel without breaking containment i.e. non-invasively. However, there needs to be a balance between achieving these benefits and obtaining the information required to ensure continued safe and reliable operation. The acceptability and benefits of non-intrusive inspection for a particular vessel will depend on a number of factors including:

- vessel geometry
- materials
- potential deterioration mechanisms and modes
- locations and sizes of flaws of concern
- process
- historic inspection data
- confidence in inspection capability
- inspection costs.

Techniques for non-intrusive inspection (NII) of equipment are becoming increasingly sophisticated and more widely available. While it may often be the preferred option, NII represents a relatively new approach by comparison to IVI and many engineers responsible for inspection planning have yet to build up experience with and confidence in its application. For the purposes of this recommended practice, IVI is considered to include the use of surface flaw detection methods such as DPI and MPI where appropriate. In addition to a general lack of experience, there are a wide variety of methods available to non-intrusively inspect equipment, each with its own specific capabilities and limitations.

This has been recognised by industry and a series of structured guidance documents have been developed Ref. [4], [5] and [6] to assist plant operators to justify and plan NII. Each of these documents deals with a specific aspect of the NII process, and there are some minor inconsistencies in notation and approach. This recommended practice is intended to bring all these documents together under a single cover, and to provide a consistent and logical approach at all stages of the non-intrusive inspection process.

Many of the recommendations in this document are not unique to non-intrusive inspection since proper planning and administration is also important for internal inspection. The document should be considered in conjunction with other relevant guidelines such as those contained in the HSE Best Practice for NDT document (Ref. [7]).

1.2 Objectives of Non-Intrusive Inspection

It is essential to be clear about the reasons for performing a non-intrusive inspection. The decision to carry out non-intrusive inspection will normally depend on a number of different factors. A primary advantage is likely to be overall cost reduction, but this may arise not because an internal inspection is replaced, but, for example, when an unscheduled inspection is required and it is hoped to avoid shutting down the plant by carrying out the inspection non-invasively. It is important to clarify the objective of the non-intrusive inspection in advance, as this may have an impact on the approach to the inspection.

Questions that should be addressed may include:

- Is the inspection to complement an internal inspection programme?
- Is the inspection intended to replace an entire internal inspection or an internal inspection regime?

Potential benefits of performing a non-intrusive inspection include:

- Avoids man access which can be hazardous (possibilities of flammable or toxic residues which can be difficult to remove, adequate lighting may be difficult to achieve).
- Planning for turnaround / shutdown. Identifying what remedial work is likely at the next turnaround? Carrying out non-intrusive inspection allows the preliminary inspection to be made before the plant is shutdown, providing an opportunity for the turnaround to be shortened by long-lead time planning and preparation (for repair and maintenance based upon the NDT results) to be made in advance of the start of the turnaround.
- Shortening the turnaround. Shutdown duration may be reduced by carrying out most or all of the inspection work in advance of the shutdown, allowing the turnaround to be restricted to mechanical work. This also simplifies planning.
- Removal of requirement to break containment. No need to isolate, drain and purge the vessel. This may include partial break of containment, for example access to water/coolant side of a heat exchanger without breaking hydrocarbon containment. This may lead to shortening of the turnaround.
- Minimises disturbances to the vessel which could create new problems.
- It may be possible to avoid the need to shut down the vessel operation entirely. Inspections can be made on a different cycle from any other maintenance, or the inspections may be made at reduced capacity or temperature, rather than having to isolate, drain and purge the vessel.
- Allows the inspection to be carried out when a potential problem is identified, without interfering with other operations. This might occur when either routine surveillance or unusual operating conditions suggest that damage might have occurred.

1.3 Scope

This recommended practice is primarily intended for those with responsibilities in the planning, implementation and acceptance of vessel inspections. It is aimed at the inspection of welded vessels constructed from metals, and related items, fittings and connections associated with them. The document is equally applicable to forged/spun metal pressure vessels, which contain no welds, as well as storage tanks and large diameter pipelines.

Although not intended to be covered by this document, some aspects of this recommended practice may also be applicable to vessels manufactured from other materials and plant items other than pressurised equipment, in which case some of the general principles developed may well still apply.

The recommended practice provides guidance for:

1) determining when NII is appropriate in principle
2) information requirements to plan for NII
3) defining the requirements for the NII method(s) to be selected
4) selecting methods that meet the requirements
5) evaluating the results of the inspection
6) documentation requirements.
The scope is limited by the following constraints.

— It is assumed that the date of the next inspection following NII will be determined in the same way as with any other inspection, based on sound engineering judgement and an understanding of the degradation rates and tolerance of the equipment to degradation. This recommended practice therefore makes no attempt to influence the timing of the next inspection, other than where the intended scope of the NII inspection has not been fully met.
— No consideration is given to the relative cost of different inspection options and the guidance process considers technical issues only.
— The recommended practice is principally for application to pressure vessels.
— The recommended practice does not address legislative requirements, which may in certain countries preclude the use of non-intrusive methods. The recommended practice considers only the technical aspects of the non-intrusive inspection planning process, and the user should confirm that any inspection plan derived using this document satisfies national legislative requirements.
— The recommended practice does not consider the impact of external degradation mechanisms, for which inspections are intrinsically non-intrusive and would be addressed by conventional assessment means.

It is also important to note that the recommended practice does not aim to comprehensively cover every aspect of planning an inspection by NII but rather seeks to provide structured guidance at key stages of the process. Although the document provides guidance on the general principles of non-intrusive inspection it is not intended to be prescriptive, and readers should assess each case point by point against their own criteria, using the document as a guideline. The recommended practice cannot and is not intended to replace sound engineering and commercial judgement by competent personnel.

It should be recognised that with any scheme of examination there is a finite probability of missing flaws or degradation which could lead to failure. This applies to both invasive and non-invasive inspection.

1.4 Overview of the Recommended Practice

Non-intrusive inspections generally require a more sophisticated approach than internal inspections. The recommended practice developed in this document recommends a systematic assessment of each item of equipment to be inspected using NII. This is a staged process which sequentially considers:

1) when and where inspection is required
2) whether NII is appropriate
3) the inspection plan
4) what inspection methods are appropriate
5) requirements during inspection
6) whether the inspection actually performed is adequate.

A summary of the recommended NII process is shown diagrammatically in Figure 1-1. The colours used on the flow chart indicate the appropriate section of this recommended practice to which the action relates.

It is important to recognise that a transfer to a non-intrusive inspection strategy is likely to require a step-change in the administration and execution of the inspection. In particular, inspection methods are likely to be more elaborate when compared with internal visual inspection. Therefore the inspection must be controlled more rigorously, with the procedures (i.e. equipment, settings and reporting criteria) carefully scrutinised and monitored at all stages in order to ensure that the inspection objectives are met. As a consequence, it is likely that planning of the inspection will need to be considerably more thorough (this is covered in Sec.4). In addition, the reporting format must be precisely specified. If the results are not requested in the correct form at the outset of the inspection or are inadequately reported, it can be difficult to transform the data to the correct format, and useful information may be overlooked or lost.
Figure 1-1
Overview of NII Procedure.
1.5 Definitions

In the context of this Recommended Practice the following definitions apply. In certain cases these definitions are the same as, or are based on, those which appear in other documents such as those of the British Personnel Certification in Non-Destruction Testing (PCN) scheme.

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>Specified zone where inspection will be carried out. In many instances this area will contain a specific feature (e.g. weld) which is of particular interest.</td>
</tr>
<tr>
<td>Capability</td>
<td>Capability is used to qualitatively describe an NDT methods’ ability to detect (POD) and size flaws.</td>
</tr>
<tr>
<td>Certification</td>
<td>Procedure used to demonstrate the qualification of NDT personnel in a method, level and industrial sector, and leading to the issue of a certificate.</td>
</tr>
<tr>
<td>Competency</td>
<td>Capability to perform a given task on the basis of education, training, qualification and experience following objective assessment. To achieve the appropriate level of competency, it may require additional training.</td>
</tr>
<tr>
<td>Corrosion risk assessment (CRA)</td>
<td>An assessment of the susceptibility of the structure under investigation to all in-service degradation mechanisms that may affect it. The CRA is not restricted to simply those degradation mechanisms related to corrosion.</td>
</tr>
<tr>
<td>Coverage</td>
<td>Defines the proportion of the structure or region thereof under consideration that is actually subject to inspection, i.e. Coverage = Area inspected / Total area under consideration</td>
</tr>
<tr>
<td>Criticality</td>
<td>A function of the risk associated with the inspected equipment, incorporating likelihood of degradation occurring and associated consequences.</td>
</tr>
<tr>
<td>Defect</td>
<td>A defect is here taken to be a flaw which renders the equipment unfit for its specified service in its current state.</td>
</tr>
<tr>
<td>Degradation mechanism</td>
<td>Those mechanisms by which integrity of the pipe or vessel could potentially be impaired e.g. erosion, fatigue, creep, brittle fracture, wall loss etc.</td>
</tr>
<tr>
<td>Effectiveness</td>
<td>A qualitative measure of the probability of detecting flaws, taking coverage into account. Effectiveness = f (POD, Coverage). Three effectiveness categories are used, (high, medium and low), these being defined by comparison to the POD for visual inspection. High implies a higher POD, medium implies a broadly similar POD and low implies a lower POD.</td>
</tr>
<tr>
<td>Feature</td>
<td>Specific part of area to be inspected i.e. weld, nozzle etc.</td>
</tr>
<tr>
<td>Flaw</td>
<td>The physical manifestation of a degradation mechanism, in terms of cracking, pitting or wall loss etc.</td>
</tr>
<tr>
<td>Inspection body</td>
<td>The organisation which manages the performance of the NDT inspection (e.g. inspection vendor).</td>
</tr>
<tr>
<td>Inspection manager</td>
<td>The plant owner’s representative with overall responsibility for the inspection.</td>
</tr>
<tr>
<td>Inspection Method</td>
<td>A specific way of applying a NDT method (e.g. Pulse echo, TOFD, Radiography etc.).</td>
</tr>
<tr>
<td>Inspection supervisor</td>
<td>The leader of the site inspection team with overall responsibility for coordinating and supervising the inspection.</td>
</tr>
</tbody>
</table>

| Internal Visual Inspection (IVI)| This is considered as an intrusive close visual examination of all internally accessible plate material and, where applicable, welds detected by magnetic particle (MPI) or dye penetrant (DPI) inspection of welds. In the context of this Recommended Practice, the term IVI is not intended to cover a less rigorous general visual examination. |
| Non-Intrusive Inspection (NII)| This refers to any inspection performed from the outside of the vessel without requiring breaks in containment and/or not requiring vessel entry. It may be performed on-stream or off-stream. The terms “non-invasive” and “non-intrusive” are often used interchangeably. |
| Operator/technician            | Qualified NDT personnel who execute the inspection. |
| Probability of detection (POD)| Probability of detecting a defined flaw type and size in the area covered by the inspection method. |
| Procedure                     | A written description of all essential parameters and precautions to be observed when applying an NDT method to a specific test, following an established standard, code or specification. |
| Qualification                  | Evidence of training, professional knowledge, skill and experience as well as physical fitness to enable NDT personnel to properly perform NDT tasks, which satisfies the requirements of EN 473 (Ref. [1]) and ISO 9712 (Ref. [2]), e.g. PCN (Ref. [3]), ASNT / TC11A. |
| Risk based inspection (RBI)    | Process of planning inspection requirements through a detailed assessment of the relative probabilities of failure and their associated consequences. |
| Work-pack                     | A complete package of documents (procedures, drawings, standards etc.) relevant to the inspection outlining scope and details of inspection to be performed. |

2. Integrity Review

2.1 General Approach

Internal visual inspection (IVI) remains widely used on the majority of vessels and several accepted procedures exist for the specification of inspection intervals to ensure safe operation. Traditionally, such intervals have been specified on the basis of legislative requirements, but increasingly plant owners take risk considerations into account in order to maximise the cost benefit of inspection. The decision to apply non-intrusive inspection methods for a particular item of equipment can depend critically on the type and extent of flaws or degradation mechanisms expected. Non-intrusive inspection methods are often slower and more expensive to apply than internal visual inspections, so that 100% inspection of a vessel is often impractical. If non-intrusive inspection (NII) is to be used in conjunction with, or as an alternative to IVI, then the inspection requirements should be defined such that the risk levels are not increased. For any given vessel this effectively means that there should not be an increase in the probability of failure (POF) when NII is used. Non-intrusive inspection therefore requires more careful consideration of the parts of the vessel to be inspected, the flaws/degradation mechanisms to be detected, and the inspection methods to be applied than is normally the case for internal (e.g. visual) inspections. Nonetheless, many of the detailed planning considerations will remain the same for NII as for IVI hence many of the traditional and more recent risk based inspection (RBI) planning approaches will remain applicable.

This section of the recommended practice is intended to provide an overview of the various data requirements that are necessary in order to be able to successfully plan for non-intrusive inspection.

2.2 Equipment Profile

The first stage of the non-intrusive inspection planning process
is to carry out a detailed review of the equipment. The intention is to ensure that the inspection planners have a comprehensive understanding of the design, operation, current condition and anticipated degradation mechanisms that may affect the equipment in service. This background information should be compiled into an equipment profile, which should form a part of the auditable document trail for the inspection. Background information that should be included in the equipment profile is as follows:

**Identity and design**
Vessel unique reference number, general arrangement drawings, materials, current design basis (pressure, temperature, corrosion allowance, cycling regime etc.)

**Type of vessel and function**
e.g. separator, heat exchanger, boiler, storage tank, blowdown vessel, reactor, etc.

**Operation and service details**
Process fluids and possible contaminants, operating temperatures, operating pressures, loading and temperature cycles, transients, excursions outside normal operating envelope, insulation systems.

**Detailed drawings**
Number and type of welds, longitudinal /circumferential shell welds, welds on the domed end/dished end, nozzles, manways, construction details including saddles, supports and support skirts, flanges, compensating plates, insulation etc.

**Modifications and repairs**
Has the vessel been modified since its original commissioning? Have any previous flaws or damage been removed or repaired (dates)? N.B. – it is important to maintain records of any such modifications or repairs.

**Previous inspection results**
Details of known/previously reported flaws/areas of degradation. Inspection methods and coverage.

**General experience**
Flaws/degradation/failures in other similar vessels (if available)

**Complementary information**
Information from corrosion monitors etc. providing evidence on whether degradation is occurring.

**Accessibility**
General accessibility, access limitations. There may be scaffolding requirements stated for each vessel. This sometimes accompanies the data held on vessels or is noted in drawings or isometrics. Though this is primarily a cost issue, there may be occasions when there are overriding factors that preclude satisfactory external access or the construction of suitable scaffolding.

**Safety Requirements**
Details should be recorded of any safety requirements pertaining to the equipment. Examples of items to consider are listed below, however any other safety related information considered pertinent to the inspection should also be recorded.

- general safety procedures
- site-specific procedures including requirements for local induction courses
- job-specific risk assessments
- local safety review requirements for equipment (at stores/safety officer)
- safety testing and certification requirements for equipment
  - Portable Appliance Testing (PAT) certification etc.
- requirement for “inherently safe” equipment
- restrictions on ionising radiations
- personal protection equipment.

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### Potential flaws/degradation
Possible flaw/degradation locations. Possible flaw/degradation morphology/sizes. Reporting criteria. (See also Sec.2.3 and 2.4 below)

The following sections describe in brief some of the established techniques used to obtain some of this information.

#### 2.3 Risk Based Inspection Approaches

Current practice is increasingly to consider the risk presented by any particular item of equipment to the plant [8] when establishing an inspection schedule. Risk based inspection (RBI) processes consider the probability of a failure of the equipment and the associated consequences in order to determine an overall risk ranking. The frequency and extent of inspection required are then set on the basis of this risk ranking. Effective RBI depends heavily on a good knowledge of the degradation mechanisms and their growth rates, the inspection history, operating conditions etc. – i.e. much of the knowledge that goes into RBI is the same as that required to enable justification and planning for NII.

#### 2.4 Corrosion Risk Assessment

Different non-intrusive inspection methods have different capabilities for detecting and sizing flaws, and therefore the inspection manager requires a more detailed knowledge of the types and locations of flaws which may be present in a particular item of equipment than is the case for an internal visual inspection. Hence, one of the key sources of information for the NII assessment is the Corrosion Risk Assessment (CRA). In practice, most rigorous integrity management systems will already incorporate a consideration of the type and likelihood of degradation expected for each vessel, as this is also a requirement for most RBI assessments.

The corrosion risk assessment is a formal review of the degradation mechanisms to which a particular plant item may be susceptible, along with a determination of the anticipated degradation rates. Typically the corrosion risk assessment will consider flaws or degradation such as:

- general corrosion over the whole area
- local corrosion
- pitting
- erosion
- general or preferential corrosion of welds (including “grooving”)
- loss of or damage to cladding or lining
- cracking under cladding or lining
- cracking in or near welds
- cracking at or near nozzles or other perforations
- cracking at or from internal fitting welds, nubs etc.
- stress corrosion cracking in parent material
- hydrogen damage (e.g. blistering, stepwise cracking)
- damage to seals, flange gasket, flange faces
- damage to internals (not normally detectable by NII).

In addition, it is important to consider the different and possibly unusual flaw morphologies which can occur (e.g. microbiological influenced corrosion) since these aspects can influence the selection and capability of non-intrusive inspection methods.

#### 2.4.1 Corrosion Risk Assessment Types

Corrosion risk assessments can be carried out at very different levels within different organisations. Given the importance of the assessment to the NII planning process, it is therefore important to be clear about what level of assessment has been carried out. The following CRA Types have been defined in order to describe the nature and extent of the CRA carried out. These CRA Types are used in the NII decision process later in this recommended practice (Sec.3).
CRA Type 1
A basic assessment considering primarily existing inspection results and expected degradation based on experience with other similar vessels. This level of assessment is what would exist as a minimum to meet inspection planning requirements by RBI. It would be carried out and reviewed by competent individuals from appropriate discipline groups including, for example, inspection, metallurgy/materials, process and engineering.

CRA Type 2
A more detailed assessment providing documented consideration of at least the following:

- the vessel's condition, based on previous inspections whenever these have been carried out
- the vessel's metallurgy, modification and repair history
- the process fluid composition and operating conditions
- corrosion management
- changes to any of the above factors that may affect inspection requirements
- types of degradation
- growth rates for each type of degradation identified as of concern (or at least some estimate related to severity, e.g. a likelihood type value from a criticality assessment)
- the locations where each type of degradation is likely to be active.

The assessment should consider existing inspection results and theoretical predictions. Theoretical predictions should be based on process and materials information.

CRA Type 3
A comprehensive assessment including an in-depth theoretical study based on process and materials information. The following issues need to be addressed:

- types of degradation
- growth rates for each type of degradation identified as of concern
- the locations where each type of degradation is likely to be active
- upset conditions that can lead to accelerated degradation
- potential for incorrect identification or omission of degradation mechanisms.

A Type 3 assessment is carried out in detail on a vessel by vessel basis.

CRA Type 4
This meets the requirements of a Type 3 assessment with respect to the theoretical study but also includes consideration of inspection results from the vessel following at least one in-service inspection. Some interpretation/correlation of the predicted degradation and condition found by inspection shall also have been carried out.

2.5 Structural Integrity Assessment
It is important to have an understanding of the equipment’s ability to resist structural damage following degradation. In its simplest form, this can be knowledge of the margins against operating conditions and corrosion allowance incorporated at the design stage. In certain circumstances however, a more comprehensive fitness for service assessment will have been carried out (for example using API 579 [9] which will provide information on, for example, critical crack dimensions. All such information provides the inspection manager with evidence as to how tolerant the equipment is to degradation, which in turn will influence the effectiveness of inspection required in order to provide assurance that failure will not occur in-service between scheduled inspections.

2.6 Operational Experience
Where the user has extensive experience with the same or similar vessels in the same or similar service, operational experience provides a very useful corroboration of the theoretical assessments described previously. Inspection histories outlining the types and sizes of any flaws found in service (or indeed the absence of flaws), give a clear indication of what inspection requirements are likely to be necessary. Of course, this is only true if the inspection carried out is appropriate for the degradation anticipated.

3. The decision guidance process

3.1 Introduction
Having carried out the integrity review and obtained the necessary information regarding the equipment condition at the time of the last inspection, it is necessary to determine whether the equipment is intrinsically suitable for non-intrusive inspection, or whether an alternative, intrusive technique such as IVI is necessary. This decision process is the second stage of the NII planning process, shown in Figure 1-1. Through application of a flow chart, the decision guidance process determines whether NII should be considered for the inspection of a given piece of equipment.

The process can be broken down into two main stages, namely screening and the high level decision process. The process is shown diagrammatically in Figure 3-1, and is described in more detail in the following sections.

3.2 Screening
The purpose of this first stage is to rapidly identify those vessels for which NII should not be considered or where the required information can not be obtained from such an inspection. The screening process is based on the user’s response to each of the following questions.

Is the vessel intrinsically suitable for NII?
Before proceeding any further with the NII decision process, it is necessary to confirm that the equipment is intrinsically suited to inspection by non-intrusive means; that is that there are no immediately obvious impediments to NII being undertaken. These include factors such as where there is no access to the vessel exterior, extreme surface temperatures, geometry constraints and restrictions to access, as well as any requirement for inspection of internal fittings.

Has the vessel previously been inspected and is the history still relevant?
Vessels with no previous in-service inspection history or for which there is reason that the inspection history may no longer be relevant (due for example to a change in process conditions) should not normally be considered for NII. There are two possible exceptions to this recommendation, as covered by the next two screening questions.

Is the vessel designed specifically for NII?
Where a vessel is designed specifically for inspection by NII, such inspection should be considered from the outset or even when conditions may have changed (while remaining within the design intent).
Is the vessel similar to others for which service history exists?
The intent of this question is to identify if there are other vessels whose inspection history may be directly relevant to the vessel under consideration. Hence the answer can only be taken as yes for vessels:

— substantially the same in terms of design, geometry, construction and conditions of service (i.e. normally empty / full, etc.).

and

— for which no factors with potential to cause a difference in the nature, distribution or rate of degradation can be identified.

Similar vessels shall be taken to mean vessels substantially the same in function, geometry, design, material and construction. Similar service shall be taken to mean substantially the same in each of chemistry, fractions and phase(s) of the vessel contents, process type(s), flow rates and temperatures. When classing vessels as similar, justification must be provided.

Is entry scheduled for other reasons?
When the vessel is to be opened for other reasons, advantage should be taken of the opportunity to perform an internal visual inspection. This does not mean that NII should not be done. However, if it is intended to do NII in parallel with IVI then this can be done without additional justification.

3.3 High-level decision process
The next step is to decide whether sufficient information exists to plan the non-intrusive inspection and what inspection effectiveness is required. This requires consideration of how confidently potential flaw types and locations can be predicted, the effectiveness of previous inspections, and the severity and rate of any known or predicted degradation. This is achieved using the high-level decision process, which determines whether NII is appropriate in principle, based largely on the use of the decision tree shown in Figure 3-2. This leads the user to a decision on whether NII is appropriate in principle based on the categories selected for each of three factors. The factors and criteria

Figure 3-1
NII Screening Procedure
for categorisation are covered below.

3.3.1 Confidence in ability to predict types and locations of degradation

The decision on whether NII is appropriate in principle is based to a large extent on confidence in being able to predict all active degradation mechanisms and hence specify methods capable of identifying the associated flaws. The ability to predict degradation mechanisms relevant to the vessel under consideration and their locations will depend on a number of factors. Evidence can be considered from two main sources, as described below:

- Theoretical: The nature of the integrity management systems employed
- Evidential: Evidence available from the same or similar vessels in the same or similar service (as defined previously).

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**Figure 3-2**
High Level Decision Guidance Chart
When using evidential information as the basis for predicting types and locations of degradation, it is important that the previous inspection results have been considered in detail at the planning stage for the current inspection and that a Type 1 CRA is in place as a minimum. The credibility of the evidence is directly linked to the amount of evidence available - i.e. number of vessels and previous inspections considered.

The confidence categories have therefore been defined as follows to consider the above factors.

**High**

Either of the following factors apply:

1) a thorough assessment of potential degradation mechanisms gives confidence that all relevant mechanisms and their likely locations have been predicted. This assessment has been carried out as part of the integrity management activity by which inspection planning is conducted. This includes as a minimum for each vessel, documented consideration of:
   - the vessel's condition, based on previous inspections
   - the vessel's metallurgy, modification and repair history
   - the process fluid composition and operating conditions
   - corrosion management
   - the degradation types, locations and rates
   - changes to any of the above factors that may affect inspection requirements.

The integrity management plan ensures consideration of the above factors by a team of competent individuals from appropriate discipline groups including, for example, inspection, metallurgy/materials, process and engineering. The CRA carried out as part of the integrity management activities described above should conform to the requirements of Type 4.

2) the user has extensive experience with the same or similar vessels in the same or similar service and inspection histories outlining the types of flaws existing are available. A detailed review of all previous inspection results has been performed. These findings have been considered in predicting the type and locations of flaws that may be expected in the current inspection. Note that extensive experience is taken to mean that data is available covering at least eight inspections in total and not less than two inspections for the longest serving single vessel used in making the judgement, at least one of which should have been a close visual inspection (internal or external depending on the nature of the degradation). In addition, a CRA shall have been carried out, this conforming at least to the requirements of Type 1.

Note that a vessel for which the operating conditions have changed since the previous inspection can not be classed as High, except where the conditions can be shown to be more benign than previously.

**Medium**

Either of the following apply:

1) a thorough assessment of potential degradation mechanisms is considered likely to predict the majority of relevant mechanisms and their locations but cannot fully rule out the possibility of additional degradation mechanisms being active. This assessment has been carried out as part of the integrity management activity by which inspection planning is conducted. It includes as a minimum for each vessel, documented consideration of:
   - the vessel's condition, based on previous inspections
   - whenever these have been carried out
   - the vessel's metallurgy, modification and repair history
   - the process fluid composition and operating conditions
   - corrosion management
   - the degradation types, locations and rates
   - changes to any of the above factors that may affect inspection requirements.

The integrity management plan ensures consideration of the above factors by a team of competent individuals from appropriate discipline groups including, for example, inspection, metallurgy/materials, process and engineering. The CRA carried out as part of the integrity management activities described above should conform to the requirements of Type 2.

2) experience, including inspection histories, is available for the same or similar vessels in the same or similar service covering not less than four inspections in total and not less than a single inspection for the longest serving vessel considered in making the judgement. A detailed review of all previous inspection results has been performed. These findings have been considered in predicting the type and locations of flaws that may be expected in the current inspection. In addition, a CRA shall have been carried out, this conforming at least to the requirements of Type 1.

Note that a vessel for which the operating conditions have changed since the previous inspection can not be classed as Medium, except where these conditions can be shown to be more benign than previously.

**Low**

Justification for inclusion in the High or Medium categories, as defined above, is not possible.

### 3.3.2 Previous inspection effectiveness

This is included as a further measure of the confidence in ability to predict all relevant flaw types and is also used in defining the effectiveness required for methods used in the current inspection as a means of ensuring the probability of failure is managed. The intent is to compare the effectiveness of the last inspection carried out relative to that of a conventional internal visual inspection, i.e. consisting of close visual examination of plate material and, where applicable, MPI or DPI.

The following category definitions apply:

**High**

The inspection performed has a better probability of detecting flaws of concern than does internal visual inspection.

**Medium**

The inspection performed offers a probability of detecting flaws of concern broadly similar to that of internal visual inspection.

**Low**

The inspection performed has lower probability of detecting flaws of concern than does internal visual inspection.

In deciding which category to select, the user must consider the following:

1) the probability of detection of the method(s) used with respect to flaws of concern. This is given by the effectiveness assigned to each method for a given flaw type.
2) the inspection coverage and how this relates to the locations of flaws of concern.

Clearly, the user’s knowledge of what flaws are likely to be of concern and where these flaws may be located is important in assigning effectiveness. For example, if it is known that flaws only occur in a particular region of the vessel and this region was fully inspected with a highly effective method then a High
inspection effectiveness may be justified. Conversely, if the user has little understanding of what flaws might exist then a high coverage inspection but using only a single method (which may be capable of detecting only one flaw type) may result in a Low ranking.

The user can consider previous inspections on similar vessels in similar service (as defined above) in determining the category to select.

### 3.3.3 Severity and rate of degradation

In making this judgement, the user will consider the worst affected zone of the vessels and the following category definitions apply.

- **High**
  
  The degradation and rate thereof is such that failure of the vessel or rejection based on inspection results can reasonably be expected within the remaining plant lifetime.

- **Medium**
  
  The degradation and rate thereof is such as to be observable during the plant lifetime but would not be expected to threaten the integrity of the vessel during this period.

- **Low**
  
  There is no degradation expected or degradation is superficial.

### 3.3.4 NII recommendation

Having answered the above questions, in conjunction with the flowchart, the suitability of the equipment for inspection by NII can be read from the chart.

### 3.4 NII Decision Record

As with all matters related to plant safety, it is essential that an auditable record is kept of all factors considered in making decisions throughout the above decision guidance process. Documentation shall cover as a minimum the following:

1) statement of any changes occurring in process that may affect the nature or rate of degradation
2) inspection reports (if not already included in the Equipment Profile)
3) justification for acceptance under screening criteria
4) list of vessels considered to be the same as the one under consideration and justification that degradation can be expected to be the same
5) justification of selection of category for:
   - confidence in ability to predict types and locations of degradation
   - previous inspection effectiveness
   - severity and rate of degradation.

### 3.5 Examples

A number of examples of application of the decision process are presented in this section.

#### 3.5.1 Heat Exchanger Vessel

A heat exchanger vessel (2-HX-05) has been in service for two years and is scheduled for its first inspection since commissioning. A decision is to be made whether this can be by NII or whether an IVI should be performed.

The following information is relevant:

- material (shell and ends): Carbon steel
- material (tubes): Stainless steel
- process fluid (shell side): Wet hydrocarbon gas with some condensation expected
- process fluid (tube side): Water.

The vessel is designed to ASME VIII Div 1 with a 3.2 mm corrosion allowance. The vessel forms part of a new process stream (Stream 2). This is similar in operation to Stream 1 (in service for a period of 10 years) but has been designed for greater efficiency and higher throughput. The vessel under consideration performs the function of two vessels (1-HX-05 and 1-HX-06) on Stream 1. Both vessels have been subject to inspection every three years. The first two inspections were by IVI but the most recent was by NII, this being regarded as at least as effective as the IVI in identifying the main degradation mechanism. The shells on both vessels are observed to suffer from mild internal corrosion. The average rate has been determined to be approximately 0.15 mm per year. The initial inspections showed that the corrosion rate does vary with position in the vessel. This is believed to be related to the gas flow rate and condensate impingement. On 1-HX-06, for example, the first inspection revealed one area with localised loss of wall thickness of 1.5 mm. An investigation carried out at the time suggested that the problem was occurring in a region of particularly high flow where water droplets were likely to be entrained. This was considered to be sufficient to remove the protective hydrocarbon rich film that would normally be expected on the steel and lead to accelerated CO₂ corrosion. An additional diverter plate was installed during the shutdown. Subsequent inspections revealed that this had resolved the problem and the region was no longer subject to higher corrosion than the remainder of the vessel.

The design of 2-HX-05 is different from that of the two vessels it replaces in requiring a higher flow rate and more complex gas flow path. In addition, the gas exit temperature is lower than that for 1-HX-06, hence the rate of water condensation is expected to be slightly higher. The feedstock for Stream 2 is nominally the same as for that for Stream 1 although it does come from a different source.

Application of the screening process (Figure 3-1):

- vessel has had previous inspection and history is still relevant? No
- vessel designed specifically for NII? No
- vessel is the same as others for which service history exists?

The response here should be No. The two vessels for which service history exists are similar in overall function but different in respect of design and process conditions and hence it is possible that the type and rate of degradation might be different. The No response at this point indicates that NII is not recommended for this vessel for the forthcoming inspection.

#### 3.5.2 Gas Receiver Vessel

A gas receiver vessel is due for its first inspection three years after entry to service. It one of ten vessels having the same design and function. Gas enters the vessels from a common line and gas take-off is to a manifold. Five of the vessels have been in service for ten years and each has had three previous inspections, the last two of which have been by NII. Inspection reports are available for each inspection performed and these have been reviewed in planning for the current inspection. The reports indicate that mild internal corrosion has been found on the interior at the bottom of each vessel. The corrosion is fairly uniform across this region in each of the vessels, with a maximum loss of wall of 1 mm on one of the vessels (the design incorporates a corrosion allowance of 5 mm). This corrosion is expected as the gas is not completely dry and a certain amount of moisture deposition occurs at the bottom of the vessel. The recent inspections by NII have included extensive wall thickness readings in the corroded regions and TOFD was undertaken on the vessel welds since fatigue cracking under the pressure cycling was identified as a possible failure mechanism. None of the TOFD tests undertaken have identified any cracking.
A decision on whether the inspection can be by NII is required as this is the preferred option.

Application of the screening process (Figure 3-1):

- vessel has had previous inspection and history is still relevant? No.
- vessel designed specifically for NII? No.
- vessel is the same as others for which service history exists? Yes, since the vessel is of the same design, is in the same service and there are no factors that would be expected to lead to differences in degradation.
- entry is scheduled for other reasons? No.

Proceeding to apply the high level decision guidance flow chart (Figure 3-2):

- confidence in ability to predict types and locations of degradation. Given that there are a large number of vessels of the same design and function and that many of these vessels have long inspection histories, the user can directly consider evidence available from these vessels in selecting the category here. Considering the option 2) (category High), in item 3.3.1, High is justified here.
- previous inspection effectiveness. The previous inspections by NII on the vessels already in service can be taken as Medium, i.e. broadly equivalent to IVI.
- severity and rate of degradation. Corrosion occurring at the same rate as on the vessels in service would not be expected to threaten the integrity of the vessels during the design lifetime, hence Medium is selected here.

Following Figure 3-2 with High, Medium, Medium, one arrives at a recommendation that NII is possible in principle.

3.5.3 Separator Vessel

A High Pressure Separator Vessel is due for an inspection. The vessel has been in service for eleven years. Its first inspection was after three years in service. The interval to the next inspection was set at four years and this interval has been retained to the present inspection. A decision on whether this inspection can be by NII is required.

The vessel is constructed of carbon steel that is clad internally with a stainless steel liner. The vessel exterior is fully insulated and the insulation is protected by galvanised steel sheet.

The integrity management plan for the plant includes technical reviews, considering the main threats to integrity, on a vessel by vessel basis. This has identified that corrosion and erosion are the only degradation mechanism of concern here. External corrosion (under the insulation) has been identified as having a higher probability than internal corrosion/erosion. However, if the carbon steel becomes exposed to the process fluids (after breakdown of the stainless steel cladding), corrosion can be very rapid hence integrity of the cladding is important. Corrosion is more likely to be in the form of pitting than of a generalised nature.

Both of the previous inspections have included visual inspection of the vessel interior. This included close visual examination of all accessible internal surfaces. All areas inspected were reported to be in good condition with no visible degradation. This information has been considered in the most recent technical review undertaken in planning for the forthcoming inspection. In order to check for signs of external corrosion, sections of insulation were removed during each of these inspections. The insulation was seen to be dry in each case and mild localised corrosion (<0.5 mm) was observed.

Application of the screening process (Figure 3-1):

- vessel has had previous inspection and history is still relevant? Yes.
- entry is scheduled for other reasons? No.

One can therefore proceed to apply the high level decision guidance flow chart (Figure 3-2):

- confidence in ability to predict types and locations of degradation. The reviews performed as part of the inspection planning process are considered to fall within the option 1) requirements for selection of this factor (see item 3.3.1, category High). The High category is selected here given that the initial conclusions of the reviews have been validated by the inspections carried out - i.e. there is now no expectation that further, as yet unidentified, mechanisms may be active.
- previous inspection effectiveness. The previous inspections by IVI can be taken as Medium.
- severity and rate of degradation. The internal inspections performed did not reveal significant degradation but corrosion (not expected to impact on vessel integrity during the remaining lifetime) was observed on the exterior. A Medium ranking therefore applies here.

Following Figure 3-2 with Medium, Medium, Medium, one arrives at a recommendation that non-intrusive inspection is possible in principle.

This vessel has jacketed external insulation hence NII meeting the efficiency requirement may not be possible unless the insulation is removed.

3.5.4 Absorber Vessel

A gas sweetener drum operates by absorption of H₂S in a zinc oxide bed. The zinc oxide becomes depleted through operation and requires replacement after some time in service. The rate of depletion depends on the nature of the gas and replacement timing is determined by monitoring the effectiveness of the sweetening based on the downstream gas composition. Replacement of the zinc oxide requires shut down of the vessel and is a complex and expensive operation. Entry for internal visual examination requires removal of the zinc oxide beds and this involves a cost almost as high as that for replacement. There are two vessels, referred to herein as A and B, running in parallel and a single vessel is capable of sweetening the entire gas throughput hence there are no production losses associated with a shut down. Nevertheless the costs of removal/replacement mean that considerable savings can be made if entry can be timed to coincide with replacement of the zinc oxide bed when it becomes necessary.

The vessels fall under an integrity management plan that uses a risk based approach to inspection planning. As part of this, an operational risk assessment was performed to identify and assess possible damage mechanisms. This indicated that internal pitting type corrosion in the wet sour gas environment is the main threat to integrity. The rate of corrosion is expected to be moderate however, and wall loss would not be expected to exceed the corrosion allowance through the vessel lifetime.

The Risk Based Inspection plan devised at the time of vessel commissioning recommended inspection by IVI at intervals of four years. After the first four years of operation, the zinc oxide showed little degradation in performance and a decision was taken to delay the IVI but perform an interim NII. Both vessels were subject to NII consisting of (a) point thickness readings at 42 shell/head and 24 nozzle locations for which pre-service measurements had been made and (b) Time of Flight Diffraction testing over each of the main longitudinal and girth welds. The thickness gauge measurements did not show any notable changes in wall thickness. No reportable flaws were identified by the TOFD inspection. Based on the results obtained, the inspection plan was revised to perform the first IVI after a further two years in operation (or sooner if a change of the zinc oxide was required).

After this two year period it is evident that the zinc oxide in both vessels has considerable remaining life hence it would be desirable to avoid opening either vessel. The decision guidance process is to be followed to establish this is possible.
Application of the screening process (Figure 3-1):
- vessel has had previous inspection and history is still relevant? Yes (NII)
- entry is scheduled for other reasons? No.

Proceed to apply the high level decision guidance flow chart (Figure 3-2):
- confidence in ability to predict types and locations of degradation. The integrity management approach and operational risk assessments performed allow option 1) to be considered in determining the category applicable here. While the operational risk assessment has considered in detail the types of degradation likely, the findings cannot be taken to be fully validated by the inspections carried out to date. It is conceivable that further, unexpected, degradation mechanisms might not have been identified by the inspection, given the limited extent of the NII carried out. Hence a Medium ranking is assigned here
- previous inspection effectiveness. The previous inspections (on both vessels) were by NII. The thickness gauge measurements did not reveal any clear loss of wall thickness. However, the operational risk study did suggest corrosion can be expected, although not sufficient to exceed the corrosion allowance through the vessel life. Hence a Medium ranking applies here
- severity and rate of degradation. The thickness gauge measurements did not reveal any clear loss of wall thickness. However, the operational risk study did suggest corrosion can be expected, although not sufficient to exceed the corrosion allowance through the vessel life. Hence a Medium ranking applies here
- the zinc oxide in vessel A remains in good condition and the thickness gauge measurements did not reveal any clear loss of wall thickness. It would be preferable to continue to operate on the basis of having performed NII rather than opening the vessel for IVI. The decision guidance process is to be followed in determining whether this is a justifiable approach.

Application of the decision guidance process:
- vessel has had previous inspection and history is still relevant? Yes (NII)
- entry is scheduled for other reasons? No.

Proceed to apply the high level decision guidance flow chart:
- confidence in ability to predict types and locations of degradation. The integrity management approach and operational risk assessments performed allow option 1) to be considered in determining the category applicable here. While the operational risk assessment has considered in detail the types of degradation likely, the findings cannot be taken to be fully validated by the inspections carried out to date. It is conceivable that further, unexpected, degradation mechanisms might not have been identified by the inspection, given the limited extent of the NII carried out. Hence a Medium ranking is assigned here
- previous inspection effectiveness. The previous inspections (on both vessels) were by NII. The thickness gauge measurements did not reveal any clear loss of wall thickness. However, the operational risk study did suggest corrosion can be expected, although not sufficient to exceed the corrosion allowance through the vessel life. Hence a Medium ranking applies here
- severity and rate of degradation. The thickness gauge measurements did not reveal any clear loss of wall thickness. However, the operational risk study did suggest corrosion can be expected, although not sufficient to exceed the corrosion allowance through the vessel life. Hence a Medium ranking applies here
- the zinc oxide in vessel A remains in good condition and the thickness gauge measurements did not reveal any clear loss of wall thickness. It would be preferable to continue to operate on the basis of having performed NII rather than opening the vessel for IVI. The decision guidance process is to be followed in determining whether this is a justifiable approach.

4. Inspection planning

4.1 Introduction

The principal objective of inspection planning is to establish a cost effective strategy which provides a satisfactory level of confidence in the vessel's safe and reliable operation until the next inspection. Inspection planning is a complex task that demands consideration of a broad spectrum of issues, ranging from detailed technical assessments of the impact of vessel operating conditions on degradation through to budget planning and allocation. As well as the technical considerations, it is generally also necessary to satisfy certain legislative requirements. While this aspect is not covered specifically in this recommended practice, since the requirements are usually country specific, it remains an important part of the planning process.

The non-intrusive inspection plan for a vessel defines which parts of the vessel should be inspected, what inspection methods should be used, and what coverage is required. This section of the recommended practice provides guidance on determining the most effective non-intrusive inspection plan for a given vessel, in terms of establishing an appropriate balance between vessel integrity and inspection cost/duration. In particular, it addresses the question of how to establish an appropriate balance between sensitive but relatively slow (and therefore expensive) inspection methods, and rapid (and therefore less expensive) but less sensitive screening methods.

Approaches to planning will vary from company to company but, typically, the plan will define at least the following:
- timing for the inspection
- type of inspection method(s) to be used
- regions of the vessel to be inspected
- shortlist of inspection service provider(s)
- qualifications of inspectors, Reporting requirements
- requirements from plant operations (e.g. shut down)
- safety requirements (equipment and personnel).

Clearly there are many additional considerations that go into the overall inspection planning activity. In particular, consideration should be given to the following:
- whether inspection to be performed on stream or off stream
- temperature during inspection (high temperature is likely to be the main concern, though difficulties may arise from the build-up of ice on low temperature items)
- whether the inspection is on the critical path of an outage?
- whether the inspection is opportunity driven?
- requirement for comparison with previous/past inspections
- cost and time constraints.

The steps in planning and implementing a non-intrusive inspection are the same, regardless of whether the inspection requirement has been determined using a risk based inspection (RBI) or more prescriptive approach. However, there can be a high degree of synergy between non-intrusive inspection and RBI since both approaches require similar types of information to be available.

The approach developed here is intended to be systematic, thereby promoting a consistent approach between operators. Nonetheless, it does not remove the need for input and review by competent personnel and the results must be reviewed by competent inspection planning personnel to check that the inspection plan is broadly consistent with their engineering judgment.

The main elements in devising an inspection plan are as follows:

Identification and selection of the planning team.

The team to plan, prepare and execute the inspection must be competent across a range of disciplines. These must be identified and appropriate personnel selected.

Definition of the inspection strategy.

The planning approach will depend in part on the intended
inspection strategy, i.e. whether the inspection is intended to confirm the absence of degradation, or to establish the depth or extent of known active degradation mechanisms.

**Definition of vessel zones.**
The vessel can be treated as one or more zones, each representing a particular combination of geometry, material, likelihood of degradation etc.

**Selection of inspection methods and coverage.**
Selection of appropriate inspection method(s) and coverage for each of the defined zones (some zones may require no inspection).
4.2 The Planning Team

Inspection planning is generally conducted by a team consisting of people with responsibilities in different areas (e.g. production, process, metallurgy, inspection, maintenance), the objective being to ensure that the inspection is effective within the constraints imposed by sometimes conflicting internal needs.

The development of a non-intrusive inspection plan can be significantly more complicated than is the case for an internal (e.g. visual) inspection. A multi-disciplinary approach is required which is likely to involve appropriate experience in engineering/materials/process operations/non-destructive testing.

The basic team required to assess the requirements for a non-intrusive inspection should consist of personnel with competencies in the following areas:

- general knowledge of the construction of containment vessels and systems, materials and materials processing, fabrication processes etc.
- corrosion or materials technology
- specific knowledge of the systems to be inspected, operational history and 'general knowledge', (knowledge of the working practices and history of the system, safety requirements, and the likely conditions at the time of inspection)
- non-destructive testing
- nominated person to coordinate the overall process.

Team members may have more than one of the specified skills; it is not necessary for the team to contain individual specialists in all of the above.

The most effective team is likely to be the smallest team that has the requisite skills, but the team should not be reduced excessively, as items are likely to be overlooked. Personnel to carry out any of these functions should be competent to assess their own level of expertise in the selected area. One member of the team should take responsibility for the overall planning process.

4.3 Inspection Strategy Type

The objective of any inspection, at the highest level, is to give a high degree of assurance that any degradation with potential to threaten integrity is detected before the next inspection. However, how it achieves that ambition will vary according to the specific details of the item under consideration. For example, the inspection regime for a vessel where the corrosion risk assessment has shown no likelihood of degradation mechanisms will be very different from the inspection regime for a vessel where stress corrosion cracking is predicted to be likely.

In the course of defining the inspection schedule the following three, closely linked, aspects must therefore be taken into consideration:

a) Degradation method:
   - nature of degradation, global wall thinning or cracking
   - location of degradation, preferential attack or more random.

b) Potential to threaten integrity (what resistance to degradation is embodied in the design)
   - corrosion allowance
   - critical crack depth.

c) Degree of assurance – feeds into the inspection performance requirements.

Any inspection program specified must also be able to give some degree of assurance that unexpected damage mechanisms are not occurring which might lead to failure of the component.

The above clearly rests on knowing what degradation mechanism to inspect for – once this is determined (through corrosion risk assessment [CRA] or historical evidence) the questions regarding assurance and potential threats to integrity can be addressed through defining where to inspect and how to inspect. These assessments must take into consideration the future operating conditions for the component, and not merely reflect past conditions. For example, where produced fluids are increasingly sour, it would be misleading to base the inspection requirements on a CRA which has assumed low sulphur content, resulting in a downplaying of the importance of inspection for mechanisms such as sulphide stress cracking (SSC).

The starting point in assessing any deviation from the specified inspection plan is an understanding of how the objectives of the inspection might be affected, e.g. does the non-conformance significantly compromise the ability of the inspection to meet the overall objectives. It is therefore important that the objectives be understood, bearing in mind that these may not be defined in detail in the inspection plan itself (as this defines the work scope for the inspection team).

As stated above, different vessels will clearly have different inspection requirements, not just in the detail of the “what, where, how”, but also in the basis of the approach. For example, a vessel for which it has been determined that generalised corrosion is the main degradation mechanism of concern but with a low probability would be treated differently to a vessel in which weld cracking by stress corrosion, such as hydrogen induced stress corrosion cracking (HISCOC) or sulphide stress corrosion cracking (SSC), is seen as a high likelihood. The differences on this level can form a useful basis for categorising they type of inspection in a way that facilitates subsequent assessment of non-conformances. To this end, three inspection types have been defined, as described in Table 4-1 below.

There is a clear difference in emphasis in each of the inspection types and this provides a useful framework for the establishment of the inspection plan, as well as in the process, treatment of any non-conformances. The three categories are discussed in more detail in the following sections, and guidance on the assignment of an inspection type to a particular item is given in Sec. 4.3.4.

<table>
<thead>
<tr>
<th>Table 4-1 Inspection Type Definitions</th>
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<tbody>
<tr>
<td>Type</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>A</td>
</tr>
<tr>
<td>B</td>
</tr>
<tr>
<td>C</td>
</tr>
</tbody>
</table>
4.3.1 Type A Inspection

Type A inspection applies in situations where there is a low probability of degradation based on previous inspection history and/or CRA and if degradation is present it will tend to be general or there is a high confidence that the most likely areas for degradation can be identified. It is also intended to provide a general screening for damage due to degradation mechanisms that might unknowingly be active. The purpose of this type of inspection is therefore primarily to confirm that there is no degradation active. If degradation is found then further steps are required to be taken.

Example of Type A

A vessel constructed in Duplex stainless steel and exposed to produced water, oil and gas at moderate temperature. The most likely mechanisms here would be chloride pitting of the shell and chloride SCC of the welds. The probability would typically be very low however, provided the chloride levels are not excessive and the temperature is moderate. In this situation the corrosion assessment would typically indicate that degradation, if it does occur, will tend to be found at the bottom of the vessel (where there is contact with water). Provided exposure to water is similar, there are no other factors leading to preferential degradation. This means there is no need to do a high coverage inspection – a fairly small coverage can give confirmation that degradation is not active. Its important however to ensure that the areas selected for coverage are likely to be representative of the worst areas. If this is possible (based on the findings of the corrosion assessment) then very low coverage may be acceptable. A key inspection performance requirement here is the ability to detect the presence of degradation, even when it is in its early stages.

1) Note that there is a sound statistical foundation for allowing this type of approach. A semi-quantitative Bayesian statistics approach can be used to show that for a situation in which there is a high level of confidence in limited degradation, a lesser amount of inspection can still have significant influence on the “degree of assurance”.

4.3.2 Type B Inspection

Type B inspection applies when there is some degradation expected but it is not expected to be such as to threaten integrity in the medium term. Medium term is in this case taken as being a period equivalent to at least two inspection intervals. This has been adopted as it allows for any missed flaws to be identified at the subsequent inspection, without threatening the integrity of the equipment. This inspection applies at a low/moderate coverage and its purpose is to provide sufficient information to allow quantified demonstration of the required degree of assurance. If the results of the inspection do not allow this then further action is taken.

Example of Type B

A vessel constructed in carbon steel and in process conditions to water is similar, there are no other factors leading to preferential degradation. The most likely mechanisms here would be chloride pitting of the shell and chloride SCC of the welds. The probability would typically be very low however, provided the chloride levels are not excessive and the temperature is moderate. In this situation the corrosion assessment would typically indicate that degradation, if it does occur, will tend to be found at the bottom of the vessel (where there is contact with water). Provided exposure to water is similar, there are no other factors leading to preferential degradation. This means there is no need to do a high coverage inspection – a fairly small coverage can give confirmation that degradation is not active. Its important however to ensure that the areas selected for coverage are likely to be representative of the worst areas. If this is possible (based on the findings of the corrosion assessment) then very low coverage may be acceptable. A key inspection performance requirement here is the ability to detect the presence of degradation, even when it is in its early stages.

4.3.3 Type C Inspection

Type C inspection applies when there is a reasonably high probability of degradation being present and/or degradation may be severe and/or degradation has no preferred locations. This inspection will often apply at moderate/high coverage. Its purpose is to give a high probability that any flaw with potential to threaten integrity is found directly. In the event that such flaws are found, then further action is required in order to accurately size the flaws to allow integrity assessments to be carried out. These more detailed, flaw specific inspections are outside of the scope for the NII inspection. The purpose of NII is primarily to identify and locate these flaws.

It is useful to illustrate, by way of examples, how the approach to inspection on different vessels aligns to the above types.

Example of Type C

A vessel constructed in carbon steel and in process conditions to water is similar, there are no other factors leading to preferential degradation. The most likely mechanisms here would be chloride pitting of the shell and chloride SCC of the welds. The probability would typically be very low however, provided the chloride levels are not excessive and the temperature is moderate. In this situation the corrosion assessment would typically indicate that degradation, if it does occur, will tend to be found at the bottom of the vessel (where there is contact with water). Provided exposure to water is similar, there are no other factors leading to preferential degradation. This means there is no need to do a high coverage inspection – a fairly small coverage can give confirmation that degradation is not active. Its important however to ensure that the areas selected for coverage are likely to be representative of the worst areas. If this is possible (based on the findings of the corrosion assessment) then very low coverage may be acceptable. A key inspection performance requirement here is the ability to detect the presence of degradation, even when it is in its early stages.

4.3.4 Selection of Inspection Type

Guidance of the selection of a particular inspection type is given in Figure 4-2 below. This considers the likelihood, extent and rate of degradation expected for a particular mechanism (based on the corrosion risk assessment) to determine the appropriate inspection type.

The inspection type categorisation is unique to a particular degradation mechanism and may also vary from one location to another. It is important, therefore that it is re-evaluated for each. For example, a vessel where the CRA has predicted both general wall loss and localised SCC cracking mechanisms might be assessed as shown in Table 4-2.

<table>
<thead>
<tr>
<th>Location</th>
<th>Damage Mechanism</th>
<th>Inspection Type</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above fluid level</td>
<td>General wall loss</td>
<td>Type A</td>
<td>Low likelihood, general in extent and medium predicted rate.</td>
</tr>
<tr>
<td></td>
<td>Localised cracking</td>
<td>Type A</td>
<td>Low likelihood, localised but would be likely to occur at welds, rate medium.</td>
</tr>
<tr>
<td>Below fluid level vessel walls</td>
<td>General wall loss</td>
<td>Type B</td>
<td>High likelihood, general in extent and medium predicted rate.</td>
</tr>
<tr>
<td></td>
<td>Localised cracking</td>
<td>Type B</td>
<td>Medium likelihood, localised but would be likely to occur at welds, rate medium.</td>
</tr>
<tr>
<td>Nozzle connection</td>
<td>General wall loss</td>
<td>Type B</td>
<td>High likelihood, general in extent and medium predicted rate.</td>
</tr>
<tr>
<td></td>
<td>Localised cracking</td>
<td>Type C</td>
<td>High likelihood, localised but would be likely to occur at welds, rate high.</td>
</tr>
</tbody>
</table>
The first stage of the assessment is to determine whether degradation of the item is likely to occur. In making this judgment the assessor should consider the worst location of the item, and take account of any previous inspection history or CRA assessment. The following categories then apply:

**Mechanism Likelihood**

*High*

Previous inspection has shown the degradation mechanism to have taken place, or the CRA indicates that the mechanism WILL take place during the remaining plant lifetime.
Medium
The CRA assessment has shown that the damage mechanism MAY take place during the equipment lifetime, but inspection history to date has shown no evidence of degradation.
Low
No degradation expected or degradation is superficial.

The next step is to consider the morphology of the damage mechanism. For the purposes of the inspection categorisation, these can be defined as either

Degradation Extent
General
Covers corrosion or erosion, where the loss of wall thickness is uniform or varies slowly within the area under consideration. It also covers crack-like flaws that are numerous and closely spaced within the area considered.

Localised (Clearly identifiable)
This covers corrosion or erosion where the loss of wall thickness is localised or irregular within the area under consideration, pitting or localised cracking which is isolated and does not merge with surrounding flaws. The principal feature is that the location of the cracking is well understood and predictable – i.e. at the weld root, and inspection can be targeted in that location.

Localised (Random)
As above, but may occur anywhere with no particular preference.

Finally, consideration is given to the rate of the degradation. Again for simplicity, the assessor is required to categorise the rate under one of three headings:

Degradation Rate
High
The anticipated rate of degradation is such that failure of the equipment or rejection based on inspection results can reasonably be expected within the remaining equipment lifetime.

Medium
The anticipated degradation rate is such that it would be expected to be observable during the equipment lifetime, but would not be expected to threaten its integrity during that time.

Low
No degradation expected or degradation is superficial.

The resultant inspection type can then be read from the flow chart. As with all aspects of the evaluation process, the result thus obtained should be considered against engineering judgement, and if necessary over-rulled, in which case a record of the decision process should be maintained.

4.4 Definition of Vessel Zones

4.4.1 Identification of Zones
Non-intrusive inspection methods have different capabilities and limitations for different geometries and materials and can be heavily influenced by aspects such as degradation and flaw types. In addition, it is generally impractical to perform non-intrusive inspection over the entire vessel surface. The approach suggested herein for the selection of methods is therefore based on the concept of “zones” representing different combinations of likelihood of degradation, tolerance to degradation and practicality of inspection. Factors such as geometry, material, likelihood of degradation, type of degradation and previous inspection results should all be considered when identifying these different zones.

This then provides the basis for deciding which parts (zones) of the vessel should be inspected, by which inspection method, and which should be subject to sample inspections. In the case of sample inspection of a zone, it may be possible to use the results to make predictions about the condition of the un-inspected part of that zone, but the results may provide little or no relevant information about the condition of other zones.

Examples of features which could be considered when dividing the vessel into zones include:

- longitudinal welds
- circumferential welds
- attachment welds
- nozzle welds
- parent plate with little probability of corrosion/erosion
- parent plate with medium probability of corrosion/erosion
- parent plate with the highest probability of corrosion/erosion (within that particular vessel)
- known corroded area in parent plate
- internal fixings with integrity impact.

Note that these are examples only, and in practice the zones should be determined by considering the detailed design, function, operating conditions and history of the vessel. The underlying principle is that each individual zone should be “homogeneous” so that any given part of a zone is representative of the rest of that zone in terms of likelihood of degradation, type of possible degradation, tolerance to degradation and type of inspection method(s) which can be applied. Inspection method and the basis for sampling (if appropriate) can then be determined individually for each zone.

Zones which are physically separate but otherwise similar can be considered as one, for the purpose of sampling e.g. in many cases no distinction need be made between spherical and cylindrical shell regions.

In order to simplify the process of defining the separate inspection zones, it is recommended that the three main aspects “design”, “operational” and “inspection history” should be considered separately.

Design and manufacturing factors
The vessel is divided into different zones (categories) based on loading conditions and tolerance to flaws. Examples include, but are not limited to: shell plates, heads/dished ends, nozzles (set on, set through and forged nozzle designs might need to be treated separately), inlets, man-ways, longitudinal welds, circumferential welds, internal attachments, internal components. Separate parts might be included in the same zone, e.g. all nozzles might belong to the same zone, welds might be included in the same zone regardless of welding process or geometry.

Operational factors
The vessel is divided into different zones reflecting the extent to which different locations are known or expected to be affected by the operating and process conditions. Considerations include, but are not limited to: service fluids, inlet/outlet locations, locations of mixed phases, high fluid flow rates and turbulence and impingement, vapour/condensation, bubbling/cavitation, pressure/pressure cycling, loading, temperature, oxidizing atmosphere, aggressive abrasive content. This requires detailed knowledge of the operational characteristics, chemical nature of the fluids, metallurgy etc. When considering the zones corresponding to operational conditions, consideration should be given to previous experience from that vessel, experience from similar vessels operating under broadly similar conditions, and generic knowledge and experience of how the vessel material behaves under the particular operating conditions (process, temperature, etc.).

Previous inspection factors
The vessel is divided into different zones corresponding to the effectiveness and results of previous inspections. Examples include, but are not limited to, regions where no previous in-service inspections have been performed, regions subjected to internal visual inspection, regions subject to ultrasonic thick-
ness measurements, regions reported to contain flaws / degradation etc.

Note that further subdivisions of zones may be necessary, e.g. regions covered by fire retardant lining, regions with limited access to inspection surface due to adjacent pipework, etc.

### 4.4.2 Example

The following example is used to illustrate the identification of zones corresponding to the different combinations.

In a partially filled vessel the shell and weld submerged in and out of the liquid and at the interface between liquid and vapour may corrode at different rates. This gives rise to a requirement for the following zones to be considered: A: Liquid zone, B: Interface zone, C: Vapour zone. Often there are specific issues relating to any nozzles or connections to vessels, so these should also be identified as individual zones, D: Inlet nozzle, F: Outlet nozzle. This would normally be sufficient to assess the vessel; however, if previous inspection records had identified a region of more advanced corrosion in a particular area of the shell (for example within the vapour region caused by condensation of vapour accelerating corrosion) than an additional zone (designated “E” in Figure 4-3 below), which is a combination of shell, vapour region, previously detected flaws would be required.

#### Zone Identifier

<table>
<thead>
<tr>
<th>Zone Identifier</th>
<th>Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Liquid phase</td>
</tr>
<tr>
<td>B</td>
<td>Interface</td>
</tr>
<tr>
<td>C</td>
<td>Vapour phase</td>
</tr>
<tr>
<td>D</td>
<td>Inlet (liquid)</td>
</tr>
<tr>
<td>E</td>
<td>Previously reported corrosion</td>
</tr>
<tr>
<td>F</td>
<td>Outlet (mixed phases)</td>
</tr>
</tbody>
</table>

**Figure 4-3**

Example of Vessel Zones

Each of the zones A to F would be considered individually for suitability for inspection by non-intrusive means.

### 4.5 Definition of Degradation Type

The next stage is to identify the type of degradation expected at each location. Degradation type should be defined according to its associated flaw morphology as this is what mostly influences the type of inspection method that will be applicable. In the majority of cases flaws can be categorised as one of the following, although judgement should always be applied as different mechanisms result in flaws with varying detectability using non-destructive methods.

- **Generalised loss of wall thickness.**
- **Localised loss of wall thickness.**
- **Localised cracking.**
- **Generalised cracking.**

In addition to the above major categories there are some less commonly encountered flaw types including de-lamination and blistering.

The user may find it helpful to develop a matrix of features and flaws to ensure that no combinations are overlooked. Table 4-3 gives an example matrix. Note that the list of features selected for inspection may not always include every feature on the vessel. Depending on the coverage requirements, there may be...
features that do not need to be included in the inspection.

Table 4-3 Example of matrix used to define feature and flaw combinations

<table>
<thead>
<tr>
<th>Vessel Feature</th>
<th>Flaw type</th>
<th>Localised LOWT</th>
<th>Generalised LOWT</th>
<th>Localised cracking</th>
<th>Generalised cracking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set on Nozzle N1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shell welds</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shell plate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saddle plate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.6 Inspection Effectiveness

Having identified the different zones within the vessel, and defined the inspection strategy (from Sec.4.3) for each zone, the inspection criticality should be determined on a zone by zone basis. The level of effectiveness which is appropriate for a particular zone will depend on the likelihood of degradation, previous inspection results, tolerance to degradation, and the consequence of vessel failure. Clearly there is likely to be a strong incentive to perform a rigorous inspection (e.g. full coverage using a sensitive inspection method which has a high probability of detecting flaws) for a part of a vessel where likelihood of degradation is high, tolerance to further degradation is low, and consequence of vessel failure is high. However less expensive methods based on rapid (but reduced sensitivity) screening methods or sample inspections might be acceptable for other zones in this vessel, or for vessels where the consequence of failure is low. Some zones may require no inspection.

By way of example, if for a particular zone, the design is such that tolerance to flaws is high, the likelihood of degradation is very low, and previous inspections have not detected any degradation, then there may be a strong justification for deciding that the inspection has a low criticality, and therefore performing only minimal inspection (or no inspection) of that zone. If on the other hand flaw tolerance is low and the likelihood of degradation is high, the inspection is critical, and obviously there is an incentive to do a much more comprehensive inspection in that particular zone.

A decision process based on a flowchart approach is presented (Figure 4-4), which provides guidance on determining the required inspection effectiveness, taking into account for each zone whether degradation has previously been detected, the likelihood of degradation (using the principles of inspection grading), current tolerance to degradation and consequence of vessel failure. The required inspection effectiveness for a particular location is read off from the appropriate strand in the flowchart.

![Figure 4-4](Inspection Effectiveness Flowchart)

**Inspection Grade**

The inspection grading system used here is taken from the principles of grading contained within the Energy Institute (formerly the Institute of Petroleum (IP)) model codes 12 and 13. [10], [11].

Equipment may be allocated a Grade between 0 and 3 based on the number of previous inspections and the rate and predictability of deterioration based on the Energy Institute guidance on the examination of pressure vessels and piping.
Grade 0
Items for which:
1) there is no historical evidence to support the judgement, or
2) the rate of deterioration is high, or
3) the rate of deterioration is unpredictable.
Items newly installed in a system commence at Grade 0.
Grade 1
Items which have:
1) at least one previous examination at Grade 0; and
2) which show a moderate rate of deterioration which is predictable.
Grade 2
Items which have:
1) at least one previous examination at either Grade 0 or Grade 1; and
2) which show a low rate of deterioration which is predictable.
Grade 3
Items which have either:
1) at least one examination at Grade 0 and one examination at either Grade 1 or 2, and which show a low rate of deterioration which is predictable; or
2) a negligible rate of deterioration in a stable service environment.

Current Tolerance to Degradation
The current tolerance to degradation should be considered in terms of whether it is low, medium or high.
In the absence of other criteria, the following definitions could apply:
Low
The known or predicted degradation and rate thereof in the zone under consideration are such that failure of the vessel (if no remedial action is taken) can reasonably be expected within the remaining plant lifetime.
Medium
The known or predicted degradation and rate thereof in the zone under consideration are such as to be observable during the plant lifetime but would not be expected to threaten the vessel during this period or require remedial action.
High
There is no degradation expected or degradation is superficial.

Consequence of Failure
The consequences of vessel failure must be considered when determining what level of inspection is appropriate for each zone, ref. [12]. For example two vessels of similar design and operating regime will experience similar degradation, however if failure of one vessel resulted in the closure of the plant for an extended period whilst repairs are undertaken, whereas for the other vessel production could continue comparatively unaffected, it is clear that the inspection of the former vessel would be specified more rigorously than that of the second.
In order to simplify the determination of consequence, it is useful to consider the health, safety and environmental consequences separately from the purely business and cost consequences. Having done so, the overall consequence ranking should be taken as whichever of these is the higher. Consequence rankings are generally determined as a part of the risk based methodology, and these can be mapped to the High, Medium and Low categories used here. Alternatively, in the absence of other criteria, the following definitions should apply:
— Health, Safety and Environmental Consequences
  High
  One or more fatalities or serious injuries requiring hospital treatment, or major release of hazardous material or pollution
  Medium
  Injury requiring hospital treatment, or release of hazardous material or pollution but with no significant effect off site.
  Low
  At most, minor injury with full recovery, or minimal release of hazardous material or pollution.
— Business Interruption and Cost Consequences
  In the absence of other criteria, the following definitions could apply:
  High
  Major shutdown / turnaround or high costs of repair / replacement
  Medium
  Several days shutdown / turnaround or significant costs of repair / replacement
  Low
  Less than one day shutdown / turnaround or low costs of repair / replacement

4.7 Required Inspection Effectiveness
The flowchart provides a “score” which represents the required inspection effectiveness for the zone under consideration. Effectiveness is here defined as a qualitative measure of the probability of detecting flaws, taking coverage into account. Assuming a uniform flaw distribution, Effectiveness = f(POD, Coverage).
Three effectiveness categories are used, (high, medium and low), these being defined by comparison to the effectiveness for visual inspection. High implies a higher effectiveness than visual inspection, medium implies a broadly similar effectiveness and low implies a lower effectiveness.
These requirements should be interpreted as follows.
Low: Spot checks. The inspection is performed at a number of discrete locations within the zone, for example manual ultrasonic thickness measurements at 500 mm intervals might be appropriate for monitoring general loss of wall thickness, or at a reduced interval for more localised corrosion/erosion.
Medium: 100% inspection of the planned inspection area using a method which has medium efficiency (>70% probability of detection), or sample inspection using a method which has high efficiency (>90% probability of detection).
High: 100% inspection of the planned inspection area using a method which has high efficiency, i.e. expected to have a probability of detection exceeding 90% for the degradation or flaws of concern.
In this context, the actual area of the zone inspected should be sufficient to allow meaningful extrapolation of the results to the un-inspected parts of that zone.
Note: The inspection requirements for a zone may need to be increased if flaws or degradation are detected during the inspection. For example if spot checks reveal greater loss of wall thickness than expected, or localised thinning, increased coverage is recommended to properly assess the extent of the thinning. If cracks are detected during a sample inspection,
100% inspection of that zone (and other susceptible zones) may be required.

4.8 Coverage

Before proceeding with selecting inspection methods, it is important to establish the nature of inspection coverage required. This, together with several other factors, has an influence on what features should be inspected, which in turn, influences what inspection methods can be selected. The decision process does not seek to guide the user to determining the exact coverage for each region of the vessel, this forms part of the detailed inspection planning activity and is discussed in more detail in Sec. 4.4:

A high level recommendation for coverage is provided below; the intent being that this is used to establish the framework into which any detailed decisions on coverage shall conform. A coverage selectiveness requirement is defined, this being such as to ensure coverage consistent with the user’s ability to predict the sites of potential flaws of concern and hence direct inspection accordingly. This is determined according to the response selected for the Confidence in ability to predict types and locations of degradation question of decision guidance process, Figure 3-2.

A High confidence will justify a minimum of Targeted coverage. Medium confidence will require a minimum of Targeted plus Exploratory coverage and Low confidence will require Global coverage. The coverage categories are as defined below:

**Targeted**

Inspection can be restricted to the sites where potential degradation has been predicted.

**Targeted plus exploratory**

Sites where potential degradation has been predicted must be inspected. In addition several further areas where it is not possible to rule out the presence of flaws must also be inspected.

**Global**

The entire area/feature of the vessel under consideration should be inspected.

As stated previously, the actual area inspected should be sufficient to allow meaningful extrapolation to remaining areas of the zone, which will be a function of the anticipated type of degradation, i.e. where general loss of wall thickness is expected, it is possible to carry out spot checks, which will rapidly confirm the current status, however where localised wall loss is expected, a more rigorous scan is required to obtain the same degree of confidence.

4.9 Selection of Inspection Method

**4.9.1 Inspection Capability**

Although routine methods and generic procedures may be appropriate for some zones (e.g. ultrasonic 0 degree wall thickness measurement, ultrasonic examination of butt welds) in other instances (e.g. where access to inspection surfaces is restricted; where complicated flaw orientations/morphologies are sought; difficult material or geometry) it may be necessary to apply specialised methods. The purpose of the inspection plan is to ensure that the correct methods are used in each context (location, degradation type and anticipated extent) in order to ensure the equipment integrity between inspections. A general description of the main inspection methods available for non-intrusive inspection of vessels, and their associated capabilities is provided in Appendix A. A variety of additional sources of information on methods exist, see for example References [13], [14], [15], [16], [17], and internet based software tools such as the HOIS Interactive Knowledge Base [18].

The nature of the degradation expected in each zone is likely to vary, as is the required inspection effectiveness. It is therefore important to consider the applicability of a particular method on a zone by zone basis. The overall objective should be to ensure that the integrity of each zone meets the minimum level needed to ensure the continued integrity required for the vessel as a whole.

**4.9.2 Inspection Method Selection Flowcharts**

Different NDT methods have differing capabilities, strengths and weaknesses. In order to facilitate the selection of the right method for the application, a number of selection flow charts have been developed for the most commonly used methods in the context of non-intrusive inspection.

The charts are intended to assist the inspection manager to determine the efficiency of a particular method in a given application, as defined by comparison to IVI, for a number of commonly used inspection methods. The method capability is classified in comparison with that of internal visual inspection, taking into consideration the degradation type. Each method is given two capability scores, one for capability in detecting flaws, and the other for the method’s ability to provide quantitative information regarding flaw size or wall thickness. For both factors, three categories are defined, namely:

- **High:** POD: The method has, in the conditions under consideration, a higher probability of detecting the flaw type than does IVI.
- **Medium:** POD: The method has, in the conditions under consideration, a probability of detecting the flaw type broadly similar to that of IVI.
- **Low:** POD: The method has, in the conditions under consideration, a lower probability of detecting the flaw type than does IVI.

In order to select a method meeting the minimum efficiency requirement, the user consults each of the flow charts, considering each factor sequentially in the following order:

**Vessel feature → Flaw type → Surface → Temperature → Thickness → Access**

The flow charts allow continuation in cases where the method is applicable for the factor considered and terminate where it is not. In each case of termination, recommendations are made for alternatives that may have a better chance of success.
Branches that do not terminate prematurely end with the efficiency rating for the method under the combination of conditions specified.

For each method a flow chart is presented which takes due consideration of vessel features, flaw type, external surface coating, temperature, wall thickness and access requirements in order to determine the likely method efficiency. A brief description of each of these factors is given below.

Features considered

The features for which guidance on the selection of an inspection method can be provided are limited to those on the baseline vessel shown in Figure 4-5 and include:

- seam and girth butt welds
- cylindrical and spherical shells
- set on and set through nozzles
- nozzle compensating plate (not shown on vessel but included)
- saddle plate (external support)
- weir plate (internal)
- lifting lug (external)
- external stiffener.

Note that several of the features are external to the vessel (compensating plate, saddle plate, lifting lug and external stiffener). The inspection method for these is recommended not in terms of assessing their external condition but in terms of the condition of the vessel interior adjacent to the feature.

Flaw types considered

At this stage only four flaw types are considered in making recommendations for inspection method. These are:

- generalised loss of wall thickness (e.g. corrosion/erosion)
- localised corrosion/erosion (e.g. pitting)
- multiple cracking (e.g. stress corrosion cracking)
- isolated cracking (e.g. fatigue cracking in welds).

External surface coating

The user selects from one of:

- bare metal
- paint
- flame or thermal sprayed aluminium
- zinc
- thermal insulation
- passive fire protection.

For bare metal it is assumed, in all cases except for when considering magnetic flux exclusion, that the exposed surface is sufficiently smooth and continuous for adequate ultrasonic transmission through conventional probes. Bare metal in a corrosive environment will often need some cleaning up before being suitable for ultrasonic inspection.

For paint it is assumed, in all cases except for when considering magnetic flux exclusion, that the coating is less than 2 mm thick and in good condition, i.e. its surface is sufficiently smooth and its body continuous so as to allow adequate ultrasonic transmission through conventional probes.

Temperature

Temperature refers to the external surface temperature of the feature under inspection, and therefore the temperature to which the inspection equipment may be exposed.

Wall thickness

Wall thickness refers to the wall thickness of the feature to be inspected (either vessel wall thickness or feature thickness as applicable).

Access requirements

The access requirements are specified as the minimum length required (i.e. dimension parallel to the surface being inspected) × the minimum height required (i.e. dimension perpendicular to the surface being inspected).

4.9.3 Inspection Method Selection Criteria

The user works through the flow charts until a method is found having at least the effectiveness rating determined in Sec.4.7. The order in which the flow charts are consulted or, indeed, whether all of the charts should be consulted in every instance cannot be prescribed. There will, for example, be cases in which the user has sufficient knowledge/experience with the inspection requirement under consideration to confidently specify an inspection method that will be suitable. In such cases only the flow chart for the selected method need be con-
sulted, with this serving as confirmation of the selection. There will also be cases where the user cannot easily identify suitable methods and in these instances it may be necessary to consult each of the flow charts. It is possible that, for the combination of factors considered, several methods will turn out to have more than the minimum efficiency required. Whilst under ideal circumstances the best method would be selected for each zone, in such cases the decision on which of the acceptable methods to use will be tempered by non-technical considerations such as cost and practicality.

In addition, it is important to consider compatibility with previous inspections. In order to be able to monitor progression of any degradation, there is clearly a need for continuity between inspections. The introduction of different inspection methods may complicate the comparison of results (particularly when changing from an invasive to a non-invasive inspection regime). The impact of any such changes can be minimised with due care in specifying the inspection reporting criteria and format.

The intent of the flow charts is to allow a rapid assessment of method capability in a particular set of circumstances. In meeting this objective they are necessarily simple and can not consider in depth all situations that might arise. There may be circumstances in which capability is significantly degraded by factors not considered in the flow charts, e.g. unusual flaw orientation, obscuration by other flaws etc. Consequently the user should regard the results of the flow charts as a guide only and should review the results obtained for each case in the context of any factors that might play a role in degrading capability in practice. Furthermore, the flowcharts reflect the typical capability of the method described and do not address improvements in performance possible through the use of specialised or custom equipment and advanced techniques.

If no method meeting the minimum requirement is available then it is recommended that the risk associated with not inspecting, or a reduced efficiency inspection of the feature for the flaw type under consideration be reviewed (see Figure 4-1). In order to show that the risk is acceptable, the review must be comprehensive and fully documented. The review should consider as a minimum:

- the probability of defects with potential to cause failure existing in the feature under consideration
- the findings of previous inspections covering the feature under consideration
- the type and extent of inspection in other regions where degradation can be expected to be similar to that for the feature under consideration
- the potential consequences of failure modes associated with the types of flaw expected in the feature under consideration.

Having identified a method which satisfies the efficiency criterion, it is worth considering whether the chosen method has the ability to size any flaws found during inspection. The outcome here might not affect the decision on whether or not to use NII for the inspection but allows early identification of the approach that may have to be adopted if flaws are found.

The process of method selection is repeated for each degradation type anticipated for the zone under consideration, and then for each zone until a compete inspection plan is established for the equipment.

It is worth noting that, in following the high level decision guidance flowchart, Figure 3-2, the effectiveness of the previous inspection has a direct effect on the requirements for the inspection being planned and may determine whether NII is recommended at all. Consequently, in planning for the current inspection the user should consider the potential implications of the effectiveness likely to be achieved on the requirements for future inspections.

**4.9.4 Statistical Methods**

In some cases, there is a requirement for the inspection planning process to involve a more quantified assessment of the risks and likelihood of failure occurring, and the impact of inspection on mitigating those risks. In particular, in some industries, there is a requirement to demonstrate that the risk exposure remains below some threshold value, typically quantified in units of probability e.g. number of failures per 10^6 years. In such cases, it is necessary to consider the statistical probability that the inspections performed will have found any degradation present, and that the most significant degradation has been accurately assessed. Reference 7 provides an insight into how inspection reduces the risk of failure, where risk of failure is a combination of likelihood of failure and consequence of failure (although Reference 7 specifically addresses ultrasonic inspection, the principles of reducing risk by inspection apply to NDT methods in general). Inspection can only reduce likelihood of failure, not consequence. For a vessel where consequence of failure is high, inspection should have the potential to maintain likelihood of failure at a low level. If the predicted likelihood of failure (without inspection) is high, then there needs to be high confidence in the capability and reliability of the inspection method to detect (and correctly sentence) flaws or degradation of concern.

Further guidance on the use of statistical methods to plan inspection activities and evaluate inspection results is given in Appendix B of this document.
**UT Thickness Gauge**

### Feature
- Butt Weld
- Cylindrical shell
- Spherical shell
- Piping

### Defect Type
- Generalised LOWT
- Localised LOWT
- Multiple cracking
- Localised cracking

### Surface
- Bare metal
- Paint
- Flame spray Al
- Zinc
- Thermal insulation
- Passive fire protection

### Temperature (°C)
- < 60 °C
- 60 – 500 °C
- > 500 °C

### Thickness (mm)
- <4 mm
- >4 mm

### Capability
- All sizes
- POD H
- Sizing H

### Notes
1. Grind weld flat
2. Consider alternative technique
3. Consider removing coating
4. Equipment must be taken off-line for inspection
5. Typical probe size down to 20 mm x 20 mm x 20 mm
### Notes

1. Grind weld flat
2. Consider alternative technique
3. Consider removing coating
4. Consider taking equipment off line for inspection

Typical equipment size:
- Mechanical scanner: from 300 mm x 300 mm x 50 mm high
- Hand-held and camera: from 20 mm x 20 mm x 20 mm plus camera line of sight.
UT Corrosion Mapping

<table>
<thead>
<tr>
<th>Feature</th>
<th>Defect Type</th>
<th>Surface</th>
<th>Temperature (°C)</th>
<th>Thickness (mm)</th>
<th>Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butt Weld</td>
<td>Generalised LOWT</td>
<td>Bare metal</td>
<td>&lt; 60 °C</td>
<td>&lt; 2 mm</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Localised LOWT</td>
<td>Paint</td>
<td>60 – 200 °C</td>
<td>&gt; 2 mm</td>
<td>H</td>
</tr>
<tr>
<td></td>
<td>Multiple cracking</td>
<td>Flame spray Al</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Localised cracking</td>
<td>Zinc</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Passive fire protection</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thermal insulation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cylindrical shell</td>
<td>Generalised LOWT</td>
<td>Bare metal</td>
<td>&lt; 60 °C</td>
<td>&lt; 2 mm</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Localised LOWT</td>
<td>Paint</td>
<td>60 – 200 °C</td>
<td>&gt; 2 mm</td>
<td>H</td>
</tr>
<tr>
<td></td>
<td>Multiple cracking</td>
<td>Flame spray Al</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Localised cracking</td>
<td>Zinc</td>
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<td>Thermal insulation</td>
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<td>Passive fire protection</td>
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<td>Spherical shell</td>
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<tr>
<td>Piping</td>
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</tbody>
</table>

Notes:
1. Grind weld flat
2. Consider alternative technique
3. Consider removing coating
4. Consider taking equipment off line for inspection

Typical equipment size:
- Mechanical scanner: from 300 mm x 300 mm x 50 mm high
- Hand-held and camera: from 20 mm x 20 mm x 20 mm plus camera line of sight.
UT Angled Pulse Echo

<table>
<thead>
<tr>
<th>Feature</th>
<th>Defect Type</th>
<th>Surface</th>
<th>Temperature (°C)</th>
<th>Thickness (mm)</th>
<th>Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butt Weld</td>
<td>Generalised LOWT</td>
<td>Bare metal</td>
<td>&lt; 60 °C</td>
<td>&lt; 8 mm</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Localised LOWT</td>
<td>Paint</td>
<td>60 – 200 °C</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Multiple cracking</td>
<td>Flame spray Al</td>
<td>60 – 200 °C</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Localised cracking</td>
<td>Zinc</td>
<td>&gt; 200 °C</td>
<td>N</td>
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<td>Thermal insulation</td>
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<td>Paint</td>
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<td>Multiple cracking</td>
<td>Flame spray Al</td>
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<td>Localised cracking</td>
<td>Zinc</td>
<td>&gt; 200 °C</td>
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<td>Thermal insulation</td>
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<td>Set-on nozzle</td>
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<tr>
<td>Set-through nozzle</td>
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<td>Compensating pad</td>
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<td>Saddle plate</td>
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<tr>
<td>Lifting lug</td>
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<tr>
<td>External stiffener</td>
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<tr>
<td>Weir plate</td>
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</tr>
</tbody>
</table>

Notes:
1. Consider alternative technique
2. Consider removing coating
3. Consider taking equipment off line for inspection
4. Consider internal inspection

Typical probe size from 20 mm x 20 mm x 20 mm
### Time of Flight Diffraction

<table>
<thead>
<tr>
<th>Feature</th>
<th>Defect Type</th>
<th>Surface</th>
<th>Temperature (°C)</th>
<th>Thickness (mm)</th>
<th>Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butt Weld</td>
<td>Generalised LOWT</td>
<td>Bare metal</td>
<td>&lt; 60 °C</td>
<td>&lt; 8 mm</td>
<td>POD H</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Paint</td>
<td>60 – 200 °C</td>
<td>&gt; 8 mm</td>
<td>Sizing H</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Flame spray Al</td>
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<td>Zinc</td>
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<td>Passive fire protection</td>
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<td>Localised LOWT</td>
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<td>Set-through nozzle</td>
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<td>Compensating pad</td>
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<td>Saddle plate</td>
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<td>Lifting lug</td>
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<td></td>
<td>External stiffener</td>
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<td></td>
<td>Weir plate</td>
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</tr>
</tbody>
</table>

#### Notes

1. Consider alternative technique
2. Consider removing coating
3. Consider taking off line for inspection

TOFD requires two probes, one either side of the inspection volume. Separation is dependant on the wall thickness

Typical probe size is 20 mm x 20 mm x 50 mm high
Medium Range UT (LORUS)

<table>
<thead>
<tr>
<th>Feature</th>
<th>Defect Type</th>
<th>Surface</th>
<th>Temperature (°C)</th>
<th>Thickness (mm)</th>
<th>Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butt Weld</td>
<td>Generalised LOWT</td>
<td>Bare metal</td>
<td>&lt; 60 °C</td>
<td>&lt; 4 mm</td>
<td>POD L</td>
</tr>
<tr>
<td></td>
<td>Localised LOWT</td>
<td></td>
<td>60 - 250 °C</td>
<td>4 - 50 mm</td>
<td>Sizing None</td>
</tr>
<tr>
<td></td>
<td>Multiple cracking</td>
<td></td>
<td>&gt; 250 °C</td>
<td>&gt; 50 mm</td>
<td>POD L</td>
</tr>
<tr>
<td></td>
<td>Localised cracking</td>
<td></td>
<td></td>
<td></td>
<td>Sizing None</td>
</tr>
<tr>
<td>Cylindrical shell</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Other techniques preferred</td>
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<tr>
<td>Spherical shell</td>
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<td>Piping (general)</td>
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<tr>
<td>Piping (restricted)</td>
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<tr>
<td>Compensating pad</td>
<td>Generalised LOWT</td>
<td>Bare metal</td>
<td>&lt; 60 °C</td>
<td>&lt; 4 mm</td>
<td>POD L</td>
</tr>
<tr>
<td></td>
<td>Localised LOWT</td>
<td></td>
<td>60 - 250 °C</td>
<td>4 - 50 mm</td>
<td>Sizing None</td>
</tr>
<tr>
<td></td>
<td>Multiple cracking</td>
<td></td>
<td>&gt; 250 °C</td>
<td>&gt; 50 mm</td>
<td>POD L</td>
</tr>
<tr>
<td></td>
<td>Localised cracking</td>
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<td>Sizing None</td>
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<tr>
<td>External stiffener</td>
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<tr>
<td>Saddle plate</td>
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<td>Lifting lug</td>
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<tr>
<td>Set-on nozzle</td>
<td>Generalised LOWT</td>
<td>Bare metal</td>
<td>&lt; 60 °C</td>
<td>&lt; 4 mm</td>
<td>POD L</td>
</tr>
<tr>
<td></td>
<td>Localised LOWT</td>
<td></td>
<td>60 - 250 °C</td>
<td>4 - 50 mm</td>
<td>Sizing None</td>
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<tr>
<td></td>
<td>Multiple cracking</td>
<td></td>
<td>&gt; 250 °C</td>
<td>&gt; 50 mm</td>
<td>POD L</td>
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<td>Localised cracking</td>
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<td>Sizing None</td>
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<td>Set-through nozzle</td>
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<tr>
<td>Weir plate</td>
<td></td>
<td></td>
<td></td>
<td>Not Suitable</td>
<td></td>
</tr>
</tbody>
</table>

Notes:
1. Consider alternative technique.
2. Consider removing coating.
3. Consider taking equipment off-line for inspection.

Typical probe sizes from 50 mm x 50 mm x 50 mm

LORUS is particularly suited to locations with limited access, and pipe supports.
A range of up to 1m either side of the probe can be inspected in one pass.
Medium Range UT (CHIME)

<table>
<thead>
<tr>
<th>Feature</th>
<th>Defect Type</th>
<th>Surface</th>
<th>Temperature (°C)</th>
<th>Thickness (mm)</th>
<th>Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butt Weld</td>
<td>Generalised LOWT</td>
<td>Bare metal</td>
<td>&lt; 60 °C</td>
<td>&lt; 4 mm</td>
<td>Y</td>
</tr>
<tr>
<td></td>
<td>Localised LOWT</td>
<td>Paint</td>
<td>60 – 250 °C</td>
<td>4 – 50 mm</td>
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<tr>
<td></td>
<td>Multiple cracking</td>
<td>Flame spray Al</td>
<td>&gt; 250 °C</td>
<td>&gt; 50 mm</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>Localised cracking</td>
<td>Zinc</td>
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<td></td>
<td></td>
<td>Thermal insulation</td>
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<td></td>
<td>Passive fire protection</td>
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<tr>
<td>Cylindrical shell</td>
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<tr>
<td>Spherical shell</td>
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<tr>
<td>Piping</td>
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<tr>
<td>Saddles plate</td>
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<tr>
<td>Lifting lug</td>
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<tr>
<td>Set-on nozzle</td>
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<tr>
<td>Set-through nozzle</td>
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<tr>
<td>Compensating pad</td>
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<tr>
<td>Wear plate</td>
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</tbody>
</table>

Notes
1. Consider alternative technique.
2. Consider removing coating.
3. Consider taking equipment off-line for inspection.

Typical probe sizes from 25 mm x 100 mm x 100 mm high.
CHIME requires two probes positioned up to 1m apart.
Recommended Practice DNV-RP-G103, October 2007

**Feature**
- Butt Weld
- Cylindrical shell
- Spherical shell

**Defect Type**
- Compensating pad
- Weir plate
- Saddle plate
- Lifting lug
- External stiffener

**Notes**
1. Consider alternative technique.
2. Consider removing coating.
3. Consider taking equipment off line for inspection.

**Typically requires a ring of probes length 500 mm height 50 mm**

**Surface Defect Type**
- Generalised LOWT
- Localised LOWT
- Multiple cracking
- Localised cracking

**Access at edges?**
- Passive fire protection
- Thermal insulation
- Zinc
- Flame spray Al
- Paint
- Bare metal

**Temperature (°C)**
- ≤ 125 °C
- > 125 °C

**Thickness (mm)**
- ≤ 50 mm
- > 50 mm

**Capability**
- POD
- None

**Other techniques preferred.**
Pulsed Eddy Current

**Feature**
- Cylindrical shell
- Spherical shell
- Piping
- Butt Weld
- Set-on nozzle
- Set-through nozzle
- Compensating pad
- Saddle plate
- Lifting lug
- External stiffener
- Weir plate

**Defect Type**
- Generalised LOWT
- Localised LOWT
- Multiple cracking
- Localised cracking

**Surface**
- Bare metal
- Paint
- Flame spray Al
- Zinc
- Passive fire protection
- Thermal insulation

**Temperature (°C)**
- < 70 °C
- 70 - 500 °C
- > 500 °C

**Thickness (mm)**
- < 6 mm
- 6 - 65 mm
- > 65 mm

**Capability**
- POD
- Sizing

**Notes**
1. Consider alternative technique
2. Consider removing coating
3. Consider taking equipment off line for inspection

Particularly suitable for vessels and pipes with lagging or insulation, or thin metallic cladding made from aluminium, stainless steel or low alloy steel. Only suitable for use on low alloy steels.

Typical probe size: 200 mm x 200 mm x 100 mm high, although specialist probes available down to 20 mm x 20 mm x 5 mm high.
Saturation Low Frequency Eddy Current (SLOFEC)

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**Feature**
- Cylindrical shell
- Spherical shell
- Piping
- Butt Weld
- Set-on nozzle
- Set-through nozzle
- Compensating pad
- Saddle plate
- Lifting lug
- External stiffener
- Weir plate

**Defect Type**
- Generalised LOWT
- Localised LOWT
- Multiple cracking
- Localised cracking

**Surface**
- Bare metal
- Paint
- Flame spray Al
- Zinc
- Thermal insulation
- Passive fire protection

**Temperature (°C)**
- < 120 °C
- > 120 °C

**Thickness (mm)**
- < 35 mm
- > 35 mm

**Capability**
- 1
- 2
- 3

---

**Notes**
1. Consider alternative technique
2. Consider removing coating
3. Consider taking equipment off line

Multi sensor scanner typically 150 mm x 150 mm x 200 mm
Passive Thermography

<table>
<thead>
<tr>
<th>Feature</th>
<th>Defect Type</th>
<th>Surface</th>
<th>Temperature (°C)</th>
<th>Thickness (mm)</th>
<th>Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylindrical shell</td>
<td>Generalised LOWT</td>
<td>Bare metal</td>
<td>Non-contact</td>
<td>&lt; 15 mm</td>
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<td>Localised LOWT</td>
<td>Paint</td>
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<tr>
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<td>Passive fire protection</td>
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<td></td>
<td>Thermal insulation</td>
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<tr>
<td>Butt Weld</td>
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<tr>
<td>Weir plate</td>
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</tbody>
</table>

Notes

1. Consider alternative technique
2. Consider removing coating

For use as an NII technique requires a process transient. Generally used to monitor insulation effectiveness.
### Radiography

<table>
<thead>
<tr>
<th>Feature</th>
<th>Defect Type</th>
<th>Surface</th>
<th>Temperature (°C)</th>
<th>Thickness (mm)</th>
<th>Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piping</td>
<td>Generalised LOWT</td>
<td>Bare metal</td>
<td>&lt; 60 °C</td>
<td>&lt; 85 mm</td>
<td>POD H</td>
</tr>
<tr>
<td></td>
<td>Localised LOWT</td>
<td></td>
<td>&gt; 60 °C</td>
<td>Special measures required</td>
<td>Use C60 or Betatron source</td>
</tr>
<tr>
<td></td>
<td>Multiple cracking</td>
<td></td>
<td></td>
<td></td>
<td>Sizing H</td>
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<td>Localised cracking</td>
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<td>Paint</td>
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<tr>
<td></td>
<td></td>
<td>Flame spray Al</td>
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<td>Zinc</td>
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<td>Thermal insulation</td>
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<td>Passive fire protection</td>
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<td>&gt; 85 mm</td>
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</tr>
</tbody>
</table>

- **Set-on nozzle**
  - POD: H
  - Sizing: H
  - Wall thickness
  - Use C60 or Betatron source

- **Set-through nozzle**
  - POD: M
  - Sizing: L
  - Wall thickness
  - Use C60 or Betatron source

- **Compensating pad**
  - POD: M
  - Sizing: L
  - Wall thickness
  - Use C60 or Betatron source

- **Lifting lug**
  - POD: L
  - Sizing: L
  - Wall thickness
  - Use C60 or Betatron source

- **External stiffener**
  - POD: L
  - Sizing: L
  - Wall thickness
  - Use C60 or Betatron source

- **Saddle plate**
  - POD: L
  - Sizing: L
  - Wall thickness
  - Use C60 or Betatron source

- **Generalised LOWT**
  - POD: H
  - Sizing: H
  - Wall thickness
  - Use C60 or Betatron source

- **Localised LOWT**
  - POD: M
  - Sizing: L
  - Wall thickness
  - Use C60 or Betatron source

- **Multiple cracking**
  - POD: M
  - Sizing: L
  - Wall thickness
  - Use C60 or Betatron source

- **Localised cracking**
  - POD: L
  - Sizing: L
  - Wall thickness
  - Use C60 or Betatron source

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**Notes**

1. Consider thickness gauge or pulse echo UT
2. Consider internal visual inspection

Requires access to both sides of equipment. Typically requires 100 mm x 100 mm and 250 mm height for source. Radiography not generally used for noninvasive inspection of vessels due to long exposure times required.
4.10 Preparation of Work-pack

The work-pack is a comprehensive package (electronic or paper based) of all relevant documentation necessary to perform the inspection. It is typically prepared by the Inspection Body (organisation which will manage the performance of the inspection), in conjunction with the owner in advance of the inspection. The work-pack will be based on the requirements of the document vessel inspection plan which defines the overall inspection strategy – see Sec.4.3. (The vessel inspection plan may be in the form of a specification which identifies the zones to be inspected, the inspection methods and the coverage required but will not include detailed procedures). The Inspection Body should review this plan and compile (as a work-pack) all of the documents required for the inspection. Collaboration with other members of the NII planning team (see Sec.4.2) may be useful.

Contents of the work-pack should include the following:

**Equipment Profile**

Details of the equipment design and operation and previous inspection history, as described in Sec.2.2, and including:

- identity and design
- type of vessel and function.
- operation and service details
- detailed drawings
- modifications and repairs
- previous inspection results
- general experience
- complementary information
- accessibility
- safety limitations
- viable degradation mechanisms
- anticipated degradation rates and extent

**NII Decision Record**

Details of the decision confirming that NII is appropriate for the equipment (Sec.3.4) including:

- statement of any changes occurring in process that may affect the nature or rate of degradation
- inspection reports (if not already included in the Equipment Profile).
- justification for acceptance under screening criteria.
- list of vessels considered to be the same as the one under consideration and justification that degradation can be expected to be the same
- justification of selection of category for:
  - confidence in ability to predict types and locations of degradation
  - previous inspection effectiveness
  - severity and rate of degradation.

**Inspection Plan**

This is the document produced by the NII planning team which is the basis of the inspection. It should contain the following information:

- details of the inspection strategy and objectives
  - including the associated decision process
- datum referencing system
- complete list of equipment zones considered and their associated flaw types
- justification shall be provided for each feature not being considered for inspection
- inspection criticality and effectiveness
- including the associated decision process
- inspection procedures and method sheets for each method
- inspection procedures must normally be written or approved by a person certified to Level 3/III in NDT
- details of the standard and extent of surface preparation
- specification of the temperature at which the inspections are to be performed together with the operating conditions (if plant is live)
- required inspection coverage
- reporting criteria and format (possibly in the form of a reporting template)
- acceptance reporting criteria and format
- well-defined thresholds or dimensions above which indications (interpreted as flaws) are recorded
- wherever possible acceptance criteria should be defined
- the reporting criteria and format should be specified in detail. The format should facilitate repeatability of the inspection and facilitate comparison between past, current and future inspection results
- recording criteria
- when it is inappropriate to define a recording level (e.g. corrosion mapping, thickness measurements) then any condition of particular interest (e.g. evidence of wall thinning) should be defined.

**Method Statement**

The Inspection Body may decide to produce a Method Statement which summarises the inspection strategy and incorporates or refers to the information described above. This will help to make the work-pack a coherent, stand-alone document. In addition, this document could account for any areas where a departure from the recommended Inspection Plan is unavoidable and describe and justify the remedial action. Other records which should be included are:

- training, qualification and certification requirements for inspection personnel
- names of the inspection team, copies of certificates
- records of any pre-inspection development work and personnel training and qualification requirements where specialised methods not covered by the general certification schemes (e.g. Ref. 3) shall be applied.

**Programme**

An outline of the inspection programme should be included to enable the detailed planning of resources. This should also include advice on any parallel activities which may impact on the timing or performance of the inspection.

Once prepared, the work-pack should be formally issued and treated as a controlled document. Relevant documents which are produced during the course of the inspection, e.g. inspection reports, should be incorporated in the work-pack, with copies sent to all those issued with controlled copies of the work-pack. When completed, the work-pack and results, together with the analysis should become part of the vessel inspection history records.

The master work-pack should be issued to the Inspection Manager who will assume responsibility for maintaining it. The work-pack should be issued in advance of the inspection to allow adequate time for inspection preparation.

4.11 Inspection Plan Review

The inspection plan forms the basis for most of the subsequent activity hence it is important that it is reviewed prior to implementation. It is good practice to include the inspection body (including their inspection technicians) in this process to...
ensure that all are fully aware of the issues. As a minimum, this review should consider the following:

- are all degradation mechanisms identified in the CRA being addressed
- has the location of potential degradation been considered in the inspection plan
- is the inspection plan consistent with the inspection Type(s) identified as applicable
- is the inspection plan consistent with the results of previous inspection(s)
- does the inspection plan include details on:
  - method
  - coverage
  - procedures
  - equipment
  - resolution
  - are there any shortcomings in terms of access, insulation removal, presence of restrictions (e.g. cable trays etc.)
  - reporting requirements.

The review process should particularly address any zones where the inspection effectiveness has been down-graded in order to enable inspection by non-intrusive methods. In particular, the impact on plant risk and subsequent inspection interval should be considered.

The inspection plans should be made available to the inspection body well in advance of the work being carried out. The purpose of this is to allow identification of potential problem areas in terms of methods and procedures specified. Likewise, the inspection plan should be made available to platform personnel as soon as possible to allow checks on possible access problems (rope access / scaffolding) to be made. It is highly recommended that a brief visual review should be carried out in order to confirm that access to the specified locations will be possible, and with sufficient space to enable efficient inspections to be performed.

The inspection body should, at this stage, be asked to provide evidence of other similar inspections successfully carried out if new methods or challenging requirements are being considered. In certain instances there may also be a need for the vendor to carry out trials to demonstrate application of the proposed method and procedure e.g. using test blocks. In this eventuality, suitable evidence should be recorded and handed to the inspection manager in order to maintain an auditable document trail.

Detailed records of the review process should be retained and incorporated into the work-pack.

5. On-site Inspection Activities

5.1 Preparation for Inspection

5.1.1 Individual Responsibilities

Preparation for the inspection will require contributions from each of the following members of the inspection team:

**Inspection Manager (the plant owner’s representative)**

To ensure that all of the parties are aware of what is expected of them, and have access to all of the relevant information. To process and act upon any feedback on the inspection work-pack.

**Inspection Supervisor (the leader of the site NDT Team)**

This is the key coordinating role. The Inspection Supervisor has many critical responsibilities and there may be a need for more than one supervisor for large scale inspections (or at least for the Inspection Supervisor to delegate some of the tasks to other team members). The Inspection Supervisor should liaise between all parties and ensure good communication.

The Inspection Supervisor should ideally be certified at least to EN473 Level 2 in the methods of NDT to be applied during the inspection. However, Level 3 certification is preferable, particularly when the Inspection Supervisor is not participating directly in the execution of the inspections. Where the method be used is outwith a certification scheme (e.g. thermography), the supervisor should be suitably experienced in the use of the chosen method.

**Other members of Inspection Team**

EN 473 Level 2 certification should normally be the minimum requirement for site inspection. However, for NII the requirements are often more specialised than covered by the general Level 2 certificate. The Inspection Body should ensure that the personnel are suitably qualified, experienced and certified where necessary for special applications.

5.1.2 Preparation Tasks

Preparation for the inspection should include the following:

**Programming/planning**

Provision of adequate resources to meet the scope of work. Coordination with parallel activities which may impact on the inspection.

Are there any restrictions to working in the area (over-the-side, time constraints, fire watch requirements)?

**Team selection**

Selection of personnel with the necessary experience, qualifications and certification. Any job-specific training requirements should be considered and dealt with (e.g. specialised ultrasonic inspection methods such as TOFD). This issue has particular relevance to NII as specialised methods not covered by standard certification schemes may be required. Evidence of general NDT competency (e.g. PCN level 2) is not necessarily evidence of competency in a specialised method and appropriate supplementary training (and occasionally examination) may be appropriate.

**Access**

Is the area to be inspected accessible for the method to be employed? This includes adequate scaffolding, inspection area within reach and sufficient clearance for personnel to access, power supply available.

Requirements for removal of lagging and insulation and, where appropriate, heat tracing to the required extent.

**Facilities**

- adequate messing facilities?
- office space for producing reports, PC working?
- storage for equipment, including power for battery charging?
- adequate protection from inclement weather conditions?
- adequate protection for equipment and personnel?
- is the area sufficiently clean and dry?
- any temperature considerations?

**Surface Conditioning**

Surface requirements stated to be checked by the local inspection supervisor and if not satisfactory then to be reported back to the inspection manager and the plant operator. Remedial action, if needed, will have to be sanctioned by the plant owner/operator, together with any making good of coatings etc. This is a critical issue for NDT, as it has a major influence on the reliability and quality of the inspection.

**Safety Issues**

Team members should be properly qualified – site safety training is normally mandatory.
Permit requirements: Is the area a designated safe area and are permits required? Are there equipment safety check requirements? (most NDT equipment is not intrinsically safe)

Local safety induction courses or medical clearance may be required prior to going on site.

Check any medical restrictions on personnel.

Pre-mobilisation Briefing

In certain circumstances, particularly difficult or off-shore inspections, it is beneficial to hold a pre-mobilisation briefing in order to familiarise the personnel involved in the inspection with the particular aspects of the inspection.

Mobilisation

Equipment should be checked in advance of shipping to the inspection site. Mobilisation to site/platform may require advance shipping of the equipment. It may be advisable to prepare a checklist of ancillary items that may be needed (tools, reporting materials, markers, spare consumables/IT consumables), check that the requisite software is installed on computers.

The team should ensure that the requirements for the equipment have been met (including calibration and certification) and that everything is in good condition, batteries charged, PAT certification satisfactory etc. before packing and shipping or mobilisation.

Start-up Meeting

All parties should meet prior to the inspection to ensure lines of communication are clear and all understand the inspection requirements and objectives.

The Inspection Team should be familiarised with the inspection, procedures, components, safety issues in a briefing session prior to the inspection.

Known areas of degradation should be identified and quantified to the NDT operator in advance of the inspection. (Change in the extent of degradation may be as important as new areas of degradation)

The role of each team member should be clearly defined.

5.2 Performing the Inspection

The Inspection Manager (or an appropriate senior delegate) should coordinate the Permit To Work system and liaise with site personnel and the inspection team.

The Inspection Manager should monitor progress against the programme and take appropriate action where necessary.

The NDT operators should comply with the agreed scope of work, and inform the supervisor of any obstructions or anomalous measurements at the earliest opportunity.

The Inspection team should practice good housekeeping both during the course of the inspections and on completion of the inspection.

When the inspection is underway, responsibility for ensuring the plan is implemented lies, in the first instance, with the inspection vendor. They should highlight as soon as possible any potential problem areas. These might include:

- access problems
- insulation not removed
- problems with surface condition
- poor sensitivity or excess noise due to material condition
- faulty equipment
- changes to procedure or methods used.

Similarly, platform inspection personnel should monitor progress of the inspection and check off work carried out against the plan. The work items can be checked off directly against the plan in terms of method, location and coverage. In addition, discussions while the inspection is being carried out should include consideration of data quality and whether this is regarded as acceptable by the technicians. The importance of this regular reporting and feedback can not be over emphasised as it allows corrective actions to be taken whilst the inspection teams are still on site.

The inspection team should be encouraged to produce interim reports on an ongoing basis. These should describe as a minimum the work items completed on the plan, any anomalies detected and any deviations from the plan.

5.3 Dealing with Non-conformances

Problems should be reported back to the integrity management team as soon as they arise. The aim should be to ensure that, wherever possible, deviations from the plan are identified prior to or during the inspection rather than when the inspection is complete. This allows direct assessment of the effects of the deviation and suitable alternatives that can be carried out as part of the current inspection to be specified.

The principles outlined in Sec. 6 should be applied to dealing with non-conformances at this stage. Every opportunity should be taken to replace any inspection that can not be carried out to the plan with a substitute inspection, using a different method or in a different location. An understanding of the Strategy Type for the particular inspection (see Sec. 4.3) is important at this stage since it affects how best to deal with the substitution. Table 5-1 below summarises the approach recommended.

Documents which evolve as the inspection progresses (e.g. inspection reports) should be added to the work-pack.

Table 5-1 Summary of approach for defining actions, according to Inspection Type, for dealing with deviations

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Inspection Type Type A</th>
<th>Inspection Type Type B</th>
<th>Inspection Type Type C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area not inspected, e.g. access problem</td>
<td>Substitute with area subject to similar conditions</td>
<td>Substitute with area subject to similar conditions</td>
<td>Attempt to overcome access restriction. If not, highlight as a non-conformance to be dealt with after the inspection is complete.</td>
</tr>
<tr>
<td>Poor technique performance, e.g. procedures not followed, incorrect calibration, poor surface condition</td>
<td>Attempt to correct and redo inspection that is affected. If not then consider substitution by alternative method giving similar performance.</td>
<td>Attempt to correct and redo inspection that is affected. If not then consider (i) substitution by alternative method giving similar performance or (ii) data analysis to check if results are acceptable.</td>
<td>Attempt to correct and redo inspection that is affected. If not then consider (i) substitution by alternative method giving similar performance or (ii) FFS type study to define minimum performance requirement.</td>
</tr>
</tbody>
</table>

Indications potentially associated with in-service degradation should also be reported to the integrity management team as soon as possible. Such indications may warrant additional inspection or a different approach (see Sec. 7).

5.4 Reporting of Results

The format for reporting NDT results will have been specified by the Inspection Management Team and defined in the work-pack.

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DET NORSKE VERITAS
Guidance is provided below.

The reporting criteria and format should be specified in detail. The format should facilitate repeatability of the inspection and comparison between past, current and future inspection results. Performa reporting formats are recommended to optimise repeatability. These should prompt the operator to enter the same type of information recommended for any routine NDT inspection.

Generally the following information should be included in the report:

1) unique report no.
2) client
3) contract name/number
4) test date(s)
5) component - title/brief description of component under test
6) dimensions - relevant dimensions of component under test
7) drawing no.
8) surface condition
9) material
10) technical details about the equipment and inspection
11) item ref. - reference/identification no. of component under test
12) inspection result - including sketches where appropriate
13) procedure no. - inspection procedure number including issue number
14) acceptance standard - including issue no.
15) test limitations and any remarks
16) clear identification of the ‘sample’ where a sample inspection only has been requested. (for example, where an entire component from a batch of similar components has been tested, the unique identity no. of the component should be reported; where only a percentage of a component has been tested the operator should report the size and location of the ‘sample’ with reference to a datum system)
17) operator’s name, signature and date of report
18) operator’s certification details (e.g. certificate no., type, expiry date)
19) inspection supervisor’s/manager’s approval
20) client approval - if required
21) any other information required by the specified procedure.

Alternatively the report format may be a customised software application, particularly where repetitive statistical information is to be recorded and analysed. Such software programmes should be designed to quickly highlight important measurements.

The approach recommended is summarised in Figure 6-1 below, and further explanation under each of the evaluation headings is given in the following sections. Where a non-conformance is identified, its impact on the effectiveness of the inspection can be evaluated using the partial factors (RFQuality and RFCoverage) approach described in Sec.7. Where no non-conformances are identified, and the inspection has been specified in accordance with references [4] and [5], then the inspection can be considered to be at least equivalent to IVI and the re-inspection date set accordingly.

6. Evaluation of Inspection

6.1 Introduction

When carrying out inspection by NII, the inspection plan will have been devised with specific objectives aimed at ensuring that the integrity requirements for the equipment, typically as defined in the RBI, CRA or hazard assessment, are satisfied. The plan forms the basis for a number of subsequent activities and it is important to have a means of evaluating work carried out by comparison to the plan. Where there are deviations from the plan these should be dealt with in a consistent way.

This section of the procedure provides guidance on evaluation of NII. It covers actions to be implemented prior to the inspection being carried out, during the inspection and on completion of the inspection. Guidance on options for justifying non-conformances and for actions following identification of critical non-conformances is also provided. Finally it provides recommendations for setting the next inspection interval, based on the existing inspection schedule or RBI assessment for the item, and the quality of the non-intrusive inspection carried out.

Evaluation forms an important activity at various stages in the approach to NII. The stages at which it is most important are highlighted in the flowchart below. This document provides further details on each of these areas.

6.2 Items to be checked for conformance

On completion of the inspection and delivery of the inspection reports, a thorough review of the reports should be carried out. This should include consideration of the following for each work item in the inspection plan:

- method
- procedure
- data quality
- location
- coverage.

The approach recommended is summarised in Figure 6-1 below, and further explanation under each of the evaluation headings is given in the following sections. Where a non-conformance is identified, its impact on the effectiveness of the inspection can be evaluated using the partial factors (RFQuality and RFCoverage) approach described in Sec.7. Where no non-conformances are identified, and the inspection has been specified in accordance with references [4] and [5], then the inspection can be considered to be at least equivalent to IVI and the re-inspection date set accordingly.

6.3 Inspection Method

Different methods have differing abilities to identify certain types of flaw. When considering whether an alternative inspection method is acceptable for a given inspection, it is important to consider the nature of the degradation expected, if any, and the ability of the new method to detect and characterise it in comparison with the method originally specified.
6.3.1 Type A inspection
A successful Type A inspection relies on a method that is sufficiently sensitive to detect early signs of degradation. If the method applied has similar POD (to that of the method specified) for the type of flaws considered as possible in the CRA, then it would normally be considered as acceptable. If, however, the POD is worse then the deviation may be considered as unacceptable or only justified after further investigation (see Sec.7).

6.3.2 Inspection Types B and C
For inspection types B and C, the method is required to sufficiently characterize any degradation present to allow a fitness for service judgement to be made. Therefore, as long as the data obtained from the new method is sufficient to demonstrate that the vessel is fit for service, then in most cases the deviation can be considered acceptable.

Guidance note:
There is one exception to this, i.e. when the technique and the way it is applied is such that there is a strong systematic overestimation of wall thickness. This possibility should be carefully considered in carrying out any statistical analysis of the data.

---e-n-d---of---G-u-i-d-a-n-c-e---n-o-t-e---

The replacement method should be considered in relation to the allowable defect sizes as determined by fitness for service considerations. This will usually mean that some compromise in performance for small flaws is acceptable.
Figure 6-1
Inspection Evaluation Flowchart
6.4 Procedure
The procedure used to carry out the inspection is likely to affect a number of inspection performance parameters including POD. The resulting evaluation is therefore very similar to that for alternative inspection methods.

6.4.1 Type A inspection
In a Type A inspection, deviations in the procedure that are unlikely to impact negatively on the POD for small flaws (of the types identified as being possible in the CRA) would normally be acceptable. However, when POD for such flaws is likely to be negatively affected, the deviation will usually be unacceptable. In certain cases it may be possible to justify deviations in procedure following a more detailed analysis (see Sec.7).

6.4.2 Type B inspection
In the case of inspections of type B, the defects to be identified are expected to be significantly smaller than the critical size, and therefore precise sizing of defects is not absolutely necessary. Hence a reduction in inspection performance is often tolerable in a Type B inspection provided it does not affect the validity of the statistical analysis. Changes in the procedure that are likely to result in a situation where there is a strong systematic overestimation of wall thickness or underestimation of crack length will not be acceptable, however, as this affects the validity of the statistical approach.

6.4.3 Type C inspection
The procedure used affects a number of inspection performance parameters including POD. In a Type C inspection it is usually the POD for relatively large flaws that is the primary concern and some compromise in the POD for smaller flaws is often acceptable. Hence, if the deviation in the procedure is unlikely to severely affect the POD for larger flaw sizes (approaching the “fitness for service (FFS)” allowable) it can be regarded as acceptable. When there is a negative impact on POD for flaws of this size the deviation would normally be considered unacceptable. However, there may be situations in which the deviation can shown to be justifiable on the basis of more detailed analysis.

6.5 Data Quality
Identification of flaws relies on interpretation of the inspection data. When carrying out manual inspection this usually has to be done on-line as the data is collected. In this case the procedure provides the main means of assurance in data quality and there is an expectation that qualified technicians will be able to recognise when problems arise. When data collection is automated, a higher level of assurance is often possible since the data can be examined in detail off-line. It is difficult to define the limits of what constitutes acceptable data quality and this, in itself, is usually determined by the NDT method. However, there are a number of factors not directly defined in the procedure (e.g. poor surface quality, system noise pick up) that can affect the data quality.

6.5.1 Type A inspection
There is an emphasis in a Type A inspection on the ability to detect signs of relatively minor degradation. Hence, reductions in data quality that are unlikely to impact negatively on the POD for small flaws (of the types identified as being possible in the CRA) would normally be acceptable. However, when POD for such flaws is likely to be negatively affected, the deviation will usually be unacceptable. In certain cases it may be possible to justify reductions in data quality following a more detailed analysis (see Sec.7).

6.5.2 Type B inspection
In the case of inspections of type B, the defects to be identified are expected to be significantly smaller than the critical size, and therefore precise sizing of defects is not absolutely necessary. Hence a reduction in data quality is often tolerable in a Type B inspection provided it does not affect the validity of the statistical analysis. Changes in data quality that are likely to result in a situation where there is a strong systematic overestimation of wall thickness or underestimation of crack length will not be acceptable, however, as this affects the validity of the statistical approach.

6.5.3 Type C inspection
The data quality directly affects a number of inspection performance parameters including POD. In a Type C inspection it is usually the POD for relatively deep flaws that is the primary concern and some compromise in the POD for smaller flaws is often acceptable. Hence if the data quality is such that it is unlikely to severely affect the POD for larger flaw sizes (approaching the FFS allowable) it can be regarded as acceptable. When there is a negative impact on POD for flaws of this size the deviation would normally be considered unacceptable. However, there may be situations in which the deviation can be shown to be justifiable on the basis of more detailed analysis.

6.6 Location
6.6.1 Type A inspection
The locations selected in a Type A inspection will have been determined as being representative of the worst regions in different zones of the vessel. If a location for inspection has been moved (e.g. due to access restrictions) to somewhere subject to similar process conditions and potential for degradation, then the deviation would normally be considered acceptable. If, however, the conditions in the new location are likely to be different from those in the location specified then the deviation would be considered unacceptable or only justifiable following further investigation (see Sec.7).

6.6.2 Type B inspection
The locations selected for a Type B inspection will have been determined as being representative of the worst regions in different zones of the vessel with the objective being to gather (statistically) sufficient data from each zone to enable an estimation of the worst potential flaws in areas not inspected. If a location for inspection has been moved (e.g. due to access restrictions) to somewhere subject to similar process conditions and potential for degradation, then the deviation would normally be considered acceptable. If, however, the conditions in the new location are likely to be different from those in the location specified then the deviation would be considered unacceptable or only justifiable following a statistical analysis that shows sufficient data has been collected for the affected zone.

6.6.3 Type C inspection
In a Type C inspection high coverage over regions or features of concern is usually a primary requirement. This will normally mean that there is little scope for accepting substitution by location. However, acceptability can sometimes be demonstrated by more detailed analysis (see Sec.7).

6.7 Coverage
6.7.1 Type A inspection
The coverage in a Type A inspection will have been determined to allow sufficient sampling of the worst regions in different zones of the vessel to give a high level of confidence that if any degradation is active, its presence is detected. Deviations that locally reduce the coverage by a small amount will normally be acceptable. However, where coverage has been reduced to the point where there is no inspection data from a particular zone or feature of concern, then the deviation would be seen as unacceptable or only justified following further investigation (see Sec.7).
6.7.2 Type B inspection
The coverage in a Type B inspection will have been determined so as to ensure (statistically) sufficient data from each zone to enable an estimation of the worst possible flaws in areas not inspected. The effects of reduced coverage normally feed directly into the statistical analysis, with reduced coverage making it more difficult to demonstrate an acceptable condition. Most instances of small amounts of reduced coverage can be dealt with on this basis. However, where coverage has been reduced to the point where there is no inspection data from a particular zone or feature of concern, then the deviation would be seen as unacceptable or only justified following further investigation (see Sec. 7).

6.7.3 Type C inspection
In a Type C inspection high coverage over regions or features of concern is usually a primary requirement. This will normally mean that there is little scope for accepting reductions in coverage. However, acceptability for small reductions in coverage can usually be demonstrated by more detailed analysis (see Sec. 7).

6.8 Critical Non-conformance
When the inspection includes a critical non-conformance, i.e. it clearly does not meet the objectives of the inspection, some action will be required to redress the situation. Each case will be dealt with on its merits but, broadly speaking, the following options can be considered:

- repeat as soon as possible the inspection work items to which the non-conformance relates
- carry out internal visual inspection as soon as possible
- repeat part or all of the NII work-scope on a shorter interval than would normally be applied
- carry out internal visual inspection on a shorter interval than would normally be applied
- apply an alternative inspection in the short term
- apply regular monitoring of wall thickness over localised areas
- place emphasis on demonstrating that the process is under control and conditions leading to excessive corrosion are not present (e.g. monitor levels of CO₂, H₂S or regular checks on corrosion coupons).

The particular circumstances will determine the best option and the associated timeframes for implementation.

6.9 Reportable Indications and flaws
In general the procedures relating to flaws are well covered by international standards (such as API 579 [9] and BS 7910 [19]) as well as company standards, and will not be dealt with in detail here. However, there are some aspects where the application of NII may lead to differences in approach under some circumstances.

For example, where a Type A inspection has been specified (i.e. no degradation is predicted) however the inspection identifies degradation, albeit below the level that would require action based on a fitness for service evaluation, then further investigation is required.

As with integrity management approaches that rely on internal visual inspection, specific actions are required when flaws are found. The Inspection Type forms a useful basis on which to define the principles governing the nature of action to be taken when flaws are found. A brief summary is provided below.

6.9.1 Type A inspection
A Type A inspection usually applies where degradation is considered unlikely and/or degradation is expected to be superficial. Hence if degradation - beyond some small limit - is found then it is likely to be sign of a process problem leading to corrosion that is more rapid than expected or it is an indication of a shortcoming in the corrosion assessment. In either event it is important to gain an understanding of the underlying cause.

This will usually depend on a greater knowledge of the nature, size and locations of the degradation than offered by the initial inspection by NII. Furthermore, given that this inspection will typically have relatively limited coverage it is important, from a direct integrity perspective, to ensure that significantly worse degradation is not present in the areas not inspected.

Given the above concerns, in most instances of flaws being detected in a Type A inspection, additional inspection to be implemented within a relatively short timeframe is warranted. This inspection should seek to increase coverage and provide detailed information on the degradation. In many instances this requirement is best met by internal visual inspection but there may be situations in which further inspection by NII is appropriate.

6.9.2 Type B inspection
An unacceptable situation in a Type B inspection is one where the probability of failure (typically based on the potential for flaws in the areas not inspected) is regarded as excessive. This can be addressed by a number of means, as described below:

- additional inspection coverage using the same method to increase the size of data set (and reduced area for which data is not available)
- inspection with the same coverage but using a method will less inherent variability in wall thickness readings. this will reduce the estimates of the worst flaw sizes
- inspection by NII or IVI with 100% coverage to identify directly the worst flaw size
- additional, more sophisticated, data analysis including correlation of results from different locations.

In many instances the first two options will be more cost effective.

6.9.3 Type C inspection
When flaws are found in a Type C inspection a detailed fitness for service assessment would normally be required unless the flaws can be directly classified as superficial. It may often be the case that the information provided in the initial NII inspection is not in itself sufficient to underpin the FFS study. Hence some additional inspection aimed at more fully characterising the flaws may be needed. This inspection may be by NII or IVI depending on the circumstances. Further action going forward would normally be defined using the findings of the FFS study as a basis.

6.10 Examples
6.10.1 Type A inspection
Within a Type A inspection the key issue is the ability to detect the presence of degradation, even when it might be in its early stages. Hence the focus in the Type A inspection will tend to be on inspection performance and this will have been used to specify the inspection method.

Non-conformances that significantly affect the performance (POD) of the inspection compared to that of the system specified will therefore potentially seriously compromise the objectives. If a system with reduced performance is used this can be compensated for to some extent by increasing the coverage but a minimum performance requirement must still be in place.

Non-conformances that relate to coverage are potentially less serious provided it is clear that the reduction/change in coverage does not entail a significant reduction in the area inspected within zones having similar operating characteristics. For example, moving a region for inspection on the bottom of a horizontal vessel longitudinally by a few hundred millimetres to allow easier access would be acceptable provided the conditions are no different to those in the area originally specified.
for inspection.

In many cases it will be location more than total area covered that is important, i.e. it may be acceptable to reduce coverage in a region of concern rather than moving the inspection to another location where conditions will be less onerous.

6.10.2 Type B inspection

Within a Type B inspection the emphasis will be on gathering sufficient information to allow a quantified statistical assessment that can be used to demonstrate a high confidence in estimating the worst flaw that might exist (including the areas not inspected). Inspection performance and coverage both affect whether the information is sufficient.

If we accept that this type of inspection forms the basis for a statistical analysis whose aim is to allow quantified assessment of vessel condition then this same statistical analysis can be used as a check on the inspection itself. Uncertainties associated with inspection system performance (e.g. poor resolution) and coverage will tend to (but not always) drive and increase in the dimensions of the worst expected flaw. Hence, if the inspection system is inherently noisy or has poor resolution, it may be difficult to demonstrate an acceptable situation. Likewise if the coverage is very low it will be more difficult to demonstrate an acceptable situation. Hence judging non-conformances will generally be straightforward for this type of inspection. There are some potential complications associated with systematic errors in the inspection system (e.g. a consistent overestimation of thickness) but these can be dealt with by carefully considered analysis of the results.

6.10.3 Type C inspection

Within a Type C inspection the emphasis is on ensuring a high probability of detecting the worst flaw, recognising that degradation may be isolated to particular regions. In many situations the dimensions of a flaw that is considered essential to detect (i.e. something with potential to grow to a size of concern within the interval to the next inspection) will be large enough to allow a reasonably high probability of detection (assuming the affected area is inspected). For example, in this type of inspection, it may sometimes be sensible to use a method that trades off a slightly lower POD for small flaws against ability to cover large areas quickly.

Since coverage will tend to be the key issue in this type of inspection, non-conformances that affect coverage will often be of most concern. There are a number of issues that affect the acceptability of coverage related non-conformances. Several of these are highlighted below:

1) Localised reduction in coverage due to local access restrictions, e.g. nozzles or pipework blocking access. In many circumstances this may be acceptable and is to be expected. For corrosion type flaws the effects can be assessed relatively simply however by establishing the acceptable loss in wall thickness for the dimensions of the area not inspected. If the metal loss elsewhere is well within the acceptable wall loss, then it may be reasonable to surmise that it is unlikely that unacceptable wall loss will have occurred in the un-inspected region; on the other hand, if measured wall loss is only just within limits elsewhere, it will be more difficult to justify the acceptability of the un-inspected area. This type of approach should take into consideration the findings of the corrosion assessment, i.e. what type of flaws are likely to be present. It will, for example, be less useful when microbial corrosion of a type that may be very localised is active

2) Significant reductions in coverage over particular areas. This will normally be unacceptable – justification here would be primarily on the basis of the corrosion review. This might reconsider the possible nature of degradation in light of the results that are available. A more comprehensive corrosion assessment for the vessel concerned may reduce some of the initial conservatism and allow the non-conformance to be acceptable.

Although inspection performance may typically be less of a concern than coverage in this type of inspection, it remains an important consideration. There will be certain minimum requirements, usually related to tolerable flaw sizes, that must be met. If the inspection system or implementation is such that these requirements are not met then the only scope for demonstrating acceptability will be to refine the definition of tolerable flaw dimensions.

7. Inspection Interval

7.1 Discussion

Sec.6 provides guidance on defining acceptability of deviations from the work-scope specified and how they can be overcome or compensated for. Once a non-conformance has been determined to be unacceptable there may be further action that can be taken to show that it remains justifiable. This section outlines briefly the types of action that may be appropriate.

This Decision Guidance Process does not usually require a very comprehensive CRA and integrity assessment to be in place before NII is deemed appropriate. It adopts a pragmatic approach consistent with the level of knowledge/information that will typically be associated with offshore pressure equipment and, consequently, the inspection requirements are usually specified conservatively.

**Guidance note:**

The Decision Guidance Process aims for practical implementation in an efficient way. In most cases the benefits (in terms of reduced workscope) of carrying out very comprehensive CRA and FFS studies on a vessel by vessel basis as a precursor to inspection planning do not justify the cost of these activities.

There are two approaches that can be used to demonstrate that the inspection carried out can be considered acceptable; firstly, comparison with internal visual inspection (IVI) and secondly, by a quantified (or semi-quantified) statistical assessment of the probability of failure. Whilst the first of these is conceptually simple, it is of necessity conservative, and it may be possible to gain further concession based on a more quantitative assessment. However, the effort and data requirements of a quantitative or semi-quantitative assessment are considerably greater. The two approaches are each discussed in more detail in the following sections.

In common will all other aspects of the NII process, it is imperative that a record is kept of all factors considered during the evaluation of the inspection. In particular, any decisions relating to the acceptance or rejection of any non-conformances identified, and the subsequent adjustment of the inspection interval must be adequately recorded in order to allow for review and checking as necessary.

7.2 Comparison with IVI

Although the first approach is widely used - and forms the basis for this recommended practice - it can be difficult to integrate in a detailed safety case since the performance of IVI is not easy to define. For this reason, the following flow charts have been developed. They guide the user in the event of a non-conformant inspection being carried out, providing a pragmatic approach to assessing the next inspection interval on the basis of the interval based on the relative effectiveness of the inspection compared to IVI.

The impact of any non-conformance in the NII process can then be evaluated in terms of a reduction in inspection interval, for example that determined by RBI and based on internal visual inspection as follows:
Where

\[ \text{Interval}_NII = RF_{\text{Quality}} \times RF_{\text{Coverage}} \times \text{Interval}_{IVI} \]

\( Interval_{NII} \) is the new inspection interval following NII
\( RF_{\text{Quality}} \) is the factor determined from Figure 7-1
\( RF_{\text{Coverage}} \) is the factor determined from Figure 7-2
\( Interval_{IVI} \) is the inspection interval based on IVI inspection

Where there is no non-conformity, the appropriate factor can be taken as 1.0, therefore a successfully completed NII inspection would have a new inspection interval equal to that for an IVI inspection.

The quality factor \( RF_{\text{Quality}} \) is a function of the ability of the inspection carried out to identify and adequately quantify any flaws present in the inspected item. It combines an assessment of the inspection method, and the parameters and procedures used as well as an assessment of the quality of the data obtained from the inspection. The assessment is by its nature judgemental and should be made by personnel experienced in the use and interpretation of the inspection methods specified and used.

The second function, the coverage factor \( RF_{\text{Coverage}} \) is a function of the actual coverage achieved in comparison with that specified at the outset. Determination of the coverage factor is described in the flowchart below, Figure 7-2. Here the issue is to ensure that sufficient material has been inspected to enable conclusions to be drawn. This is particularly important where the CRA predicts that corrosion will take place in a particular area, for example at an inlet nozzle.

By following the logic of the appropriate chart, the two factors can be evaluated and the revised inspection interval determined as a proportion of the normal inspection interval based on RBI considerations combined with internal visual inspection.

It is important that any inspection interval determined on the basis of the charts in Figures 7-1 and 7-2 should be reviewed by competent staff to ensure that all relevant facts have been adequately taken into account in setting the revised interval. In particular, it should be noted that the factors embodied in the charts are based on a judgemental assessment of the impact of a particular deficiency for “typical” situations. Where such situations do not exist, it is likely that the reduction factors would need to be adjusted accordingly. The results of the review process and any amendments to the inspection interval should be recorded and retained for QA audit purposes.
Figure 7-1
Evaluation of Method / Performance Non-conformances
7.3 Detailed Assessment

Where it is not possible to justify the non-conformance on the basis of the above comparison with IVI, a quantitative or semi-quantitative approach may enable a given non-conformance to be justified. These assessments cover three main areas, i.e.

— corrosion engineering
— inspection performance
— structural integrity.

A reduced inspection work-scope would usually be justifiable following a very comprehensive CRA and integrity assessment that would consider the worst sizes of flaws expected, the distribution of flaws, growth rates and allowable flaw sizes.

Detailed guidance on how to assess fitness for service (or probability of failure) of a vessel, given information on corrosion conditions and inspection performance, is beyond the scope of this document. Guidance on fitness for service assessment is covered in detail in a number of codes and standards (e.g. BS7910, API 579) and this can form the basis for a probabilistic approach including consideration of inspection performance measures. A number of approaches, different in terms of detail, are applicable and will be appropriate in different cir-

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**Figure 7-2**
Evaluation of Non-conformance in Coverage / Location
cumstances. This document includes a brief summary of the key elements of the type of approach that can be adopted.

The starting point for the assessment will typically be a detailed corrosion review. This would normally consider some or all of the following:

- process conditions (chemistry, temperatures, pressures, dew-points)
- materials
- types of degradation (e.g. pitting, general corrosion
- locations of degradation
- growth rates
- upset conditions
- effects of controls including inhibitors
- monitoring activities
- inspection and maintenance history.

The aim of the corrosion study should be to provide an informed view on the likely types of degradation, their locations, their distribution and the worst expected sizes at present and going forward over the interval to the next inspection.

An assessment of the performance of the inspection actually carried out with respect to the types of flaw identified in the corrosion review is also usually necessary. The key aspect to be considered is the probability of detection for a range of flaw sizes and distributions. This should include, where possible, consideration of the coverage and likely spatial distribution of the flaws (e.g. is degradation likely to be localised or more randomly distributed). Note that the emphasis will be different according to inspection type however and the following broadly applies:

- in a type a inspection the key concern is on the ability to detect early signs of degradation. hence the probability of detection should relate to finding sufficient signs of degradation to conclude that degradation is indeed present (since this is what would trigger further action)
- in a type b inspection there is a lesser emphasis on pod directly. however, it remains essential that the inspection system is unlikely to systematically overestimate wall thickness. for this reason, it is important to have an understanding of the likely back wall surface morphology and any limitations this can impose on the recording of thickness data (depending on scan increment for example)
- in a type c inspection it is typically the ability to detect larger flaws that is the primary concern. for such inspections the flaws are potentially isolated so the pod should related to isolated flaws rather than finding signs of degradation within a larger flaw population.

The integrity assessment brings together the corrosion and inspection information to develop an estimate of the probability of flaws, with potential to threaten integrity of the vessel, having been missed in the inspection. This relies on estimates of the allowable defect sizes (as defined by fitness for service considerations) and comparison with the flaw sizes that may have escaped detection during the inspection.

The final outcome of the assessment should normally be an estimate of the effects of the inspection actually carried out on the level of assurance. If this is not considered acceptable then further action (usually in the form of inspection) will be required in addressing the non-conformance.

7.4 Examples

The following example cases were used in order to validate the evaluation approach described in this section. A number of actual NII assessments which had used the recommended practice in establishing the validity and scope of inspection were reviewed. For each example, the steps in the evaluation are presented and the resulting reduction in inspection interval considered in comparison with engineering judgement.

Clearly, as with the entire NII process, inspection validation requires engineering judgement to be used at all stages. All available information should be used in order to assess the value of the inspection carried out and sole reliance should not be placed on the mechanistic approach presented in the guidelines. The examples quoted here, however, demonstrate that under normal circumstances the approach will give appropriate assessments.

The remaining sub-sections of this section describe the background and resulting evaluation for the various validation cases.

7.4.1 Glycol Contactor

Background information

Installation date: 1995

Date: Feb. 1995
Type of inspection: Internal visual – baseline inspection.
Summary of findings: Nothing significant in unlined section. A holiday noted in coating near one of the nozzles in the lined section. This was repaired.

Date: May 1998
Type of inspection: Internal visual.
Summary of findings: Lining in good condition. Shell plates in good condition, some corrosion deposits noted on surface near middle section.

Expected degradation

Internal corrosion is primary mechanism of concern (CRA predicts 0.99 mm/yr loss for the contactor section and the corrosion rate in middle section just above the lined section may be expected to more than double.). Inspection (IVI May 1998) confirmed presence of corrosion deposits in middle section but there was no measurable depth of corrosion loss.

External corrosion, Stress corrosion cracking and Wet H₂S cracking identified as low probability. No cracking identified by inspections to date.

Failure of lining could potentially lead to rapid corrosion hence integrity of lining is very important.

Similar vessels

This is the only vessel of this type on the platform.

Specified IVI Work-scope

The work-scope for traditional internal visual inspections includes inspection of the entire surface of the pressure retaining envelope, including man-way doors and necks, nozzle bores and nozzle welds. N.B. Some areas of the internal surface are inaccessible due to the presence of internals which are not removed during shutdowns. Following the 1998 inspection, the period was set at 5 years.

NII Inspection Plan

Following the H0IS decision guidance procedure, it was concluded the vessel was suitable for inspection by NII given the margin against perforation assuming conservative corrosion rates (approximately 5 years). The following inspection plan was specified for unlined sections of the vessel:

Corrosion mapping at standard resolution of the following areas:

1) vessel top head: 1 off 300 mm × 300 mm area adjacent to top nozzle. 
   (Region 1 of Figure 7-3)
2) strake 6: 4 off 300 mm × 300 mm areas at cardinal positions. 
   (Region 2 of Figure 7-3)
3) strake 5: 4 off 300 mm × 300 mm areas at cardinal positions. 
   (Region 3 of Figure 7-3)
4) strake 4: 4 off 300 mm wide vertical bands from 200 mm below chimney tray to 200 mm above packing tray. (Region 4 of Figure 7-3)

5) strake 4: Circumferential band 300 mm high centred on packing tray. (Region 5 of Figure 7-3).

Figure 7-3
Glycol Contactor Inspection Locations

In addition to the corrosion mapping, time of flight UT inspection (TOFD) was carried out on the lined section and nozzles.

Inspection Evaluation

Determination of Inspection Type

The inspection type is determined following the guidance of Figure 3-2 of the procedure. In this case, the corrosion mapping inspection is intended to confirm that the extent of internal corrosion has remained within expected and acceptable limits.

Given that the CRA has predicted that internal corrosion will take place and that corrosion debris was identified during the previous inspection, the flowchart is entered on the “high likelihood” of degradation.

For internal corrosion, the extent of degradation is typically uniform, and “General” can be selected. The CRA predicted corrosion rates in excess of 0.99 mm/year in the event of coating failure at the, at which rate integrity of the vessel is predicted to be compromised in around 5 years. The degradation rate is therefore taken as “High”, and the inspection type is therefore given as “Type B”.

Determination of Inspection Interval

The inspection was carried out in full, using the intended inspection methods. Following the evaluation flowchart (Figure 6-1), no reduction in the proposed future inspection interval is therefore required. This is clearly what would be expected, and the evaluation procedure correctly leads to a satisfactory conclusion.

7.4.2 Glycol Flash Drum

Background information

Inspection History

Start up date: 1996

Date: Jan. 1995
Type of inspection: Internal visual – baseline inspection.
Summary of findings: Shell and head plates in good condition.

Date: Oct. 2001
Type of inspection: External thermal survey.
Summary of findings: No significant problems.

Expected degradation

Internal corrosion, External corrosion, Stress corrosion cracking and Wet H2S cracking identified as low probability in CRA. No corrosion or cracking observed during previous inspections.

Similar vessels

This is the only vessel of this type on the platform.

Specified IVI Work-scope

The specified IVI work-scope was for internal visual inspections of the vessel heads shell plates, man-way door, nozzle bores and attachment welds.

NII Inspection Plan

Following the HOIS decision guidance procedure, it was concluded that the vessel was suitable for inspection by NII using a method with medium efficiency as no mechanisms leading to high probability of failure were identified either by previous inspection or corrosion assessment. However, credible mechanisms include:

- corrosion – some internal corrosion may be present. If so, it is anticipated at the liquid level and would be expected to be more advanced at the inlet end of the vessel. No particular susceptibility for corrosion of nozzles (except inlet nozzle) or welds in preference to parent material
- stress corrosion cracking and Wet H2S cracking identified as low probability in CRA.

The proposed NII work-scope was therefore as follows:

**Vessel shell**

- Corrosion mapping of one 300 mm × 300 mm area per shell plate at standard resolution at TDC.
- Corrosion mapping of 100% of top half of inlet side vessel head to 300 mm below centreline.
- Corrosion mapping of a band 600 mm wide along centreline of vessel for full length of strake 1 (closest to inlet nozzle).
- Corrosion maps 600 mm high by 300 mm wide astride strake 2/3 circ. weld. Both sides of vessel at vessel centreline.
- Corrosion map 600 mm high by 300 mm wide astride strake 2/3 circ. weld. Both sides of vessel at vessel centreline.
- TOFD inspection of all main shell circ. welds from 300 mm above vessel centreline to 300 mm below, both sides of vessel.
- TOFD inspection of all main vessel shell weld long/circ. tee intersections for 300 mm along each leg.

**Nozzles**

- Grey scale 0° axial B-scans at 90° intervals around inlet nozzle circumference or corrosion map of nozzle material.
Inspection Evaluation

Determination of Inspection Type

The inspection type is determined separately for the two degradation methods considered, internal corrosion and cracking, using the flowchart in Figure 3-2 of the procedure.

As the CRA identified no corrosion mechanisms leading to a high probability of degradation, the flow chart is entered at the “Low likelihood” spine. Corrosion is generally either “General” or “Localised” in extent. In order to present a conservative assessment, in this case “Localised” has been assumed. The corrosion rate is taken as “low” given the results of the CRA, which gives an inspection type of “Type A” for the corrosion mapping.

For the cracking mechanisms, the CRA predicted a “Low likelihood”. By their nature, stress corrosion and wet H₂S cracking mechanisms principally occur in regions of highest stress, and thus the location is “Likelihood – clearly defined”. Cracking can proceed rapidly, impacting on vessel integrity within its planned life, thus “High rate” is chosen. This gives an inspection type of “Type B” for the corrosion mapping.

Determination of Inspection Interval

A number of the corrosion mapping inspections on the northern side of the vessel were unable to be carried out for reasons of accessibility. Following the flowchart in Figure 6-1 of the procedure, the inspection was carried out using the correct methods and procedures, thus the quality factor is taken as 1, however the coverage factor needs to be determined using Figure 7-2.

The un-inspected regions (Regions 7, 8, 9, 10, 18 and 19) are expected to experience similar conditions to the corresponding regions on the southern side of the vessel (i.e. Regions 1, 2, 3, 4, 5, 6). The scans do however cover directly the primary zone of concern on the end, i.e. the liquid line, and a large proportion of the total head area and the results presented do not show any signs of significant corrosion. Following the flowchart in Figure 7-2 the coverage factor is determined as 0.5 as follows:

The area missed is deemed to include areas of concern (i.e. liquid line) but areas of similar susceptibility have been successfully inspected with no indications. The total area of those not inspected is estimated to be between 25 and 50% of the originally specified zones. For a type A inspection, this gives a coverage factor of 0.5.

Similarly, a number of the planned TOFD inspections were not able to be carried out; however in this case, manual UT inspections were carried out instead. In evaluating this inspection, therefore, the quality factor is evaluated using Figure 7-1. In this case, the inspection is a type B inspection to determine that any cracks present are below critical size (i.e. the inspection objective is to determine the size of defects). UT does not imply a systematic over estimation of defect size, and as no flaws were found during the inspection (let alone defects in excess of 50% of critical), this results in a quality factor of 0.5 for the cracking mechanism inspection.

In both cases, corrosion and cracking, the evaluation has determined that further inspection should be carried out at a reduced interval. In this case, the guidance suggests that the interval should be half that intended based on the original inspection scope. In practice, further inspection of the vessel was scheduled for the following year. Once again, the evaluation procedure has arrived at a suggested interval which is in agreement with that actually determined for the plant on the basis of engineering judgment alone.

7.4.3 Vent Knock Out Drum

Background information

Inspection History

Start up date: 1996
Date: Jan. 1995
Type of inspection: Internal visual, video only – baseline inspection.
Summary of findings: Some rust staining identified, but no evidence of significant wall loss. No evidence of cracking.

Expected degradation

Internal corrosion, External corrosion, Stress corrosion cracking and Wet H₂S cracking identified as low probability in OCA. No cracking observed during inspections but evidence of corrosion (rust staining) observed during internal video survey. No significant loss of wall however in UT thickness measurements.

Similar vessels

This is the only vessel of this type on the platform.

IVI Work-scope

The specified IVI work-scope was for internal visual inspections of the vessel heads shell plates, man-way door, nozzle bores and attachment welds.

NII Inspection Plan

The HOIS decision guidance procedure concludes that the ves-
Determination of Inspection Interval

The inspection type is determined separately for the two degradation methods considered, internal corrosion and cracking, using the flowchart in Figure 3-2.

As previous inspection indicated the presence of rust staining, the flow chart is entered at the “High likelihood” spine. Corrosion is predicted by the CRA to be “General” in extent, but with a “low” corrosion rate. This gives an inspection type of “Type A” for the corrosion mapping.

For the cracking mechanisms, the CRA predicted a “Low likelihood”. By their nature, stress corrosion and wet H_2S cracking mechanisms principally occur in regions of highest stress, and thus the location is “Likelihood – clearly defined”. Cracking can proceed rapidly, impacting on vessel integrity within its planned life, thus “High rate” is chosen. This gives and inspection “Type B” for the weld inspections.

Determination of Inspection Type

The inspection type is determined separately for the two degradation methods considered, internal corrosion and cracking, using the flowchart in Figure 3-2.

As previous inspection indicated the presence of rust staining, the flow chart is entered at the “High likelihood” spine. Corrosion is predicted by the CRA to be “General” in extent, but with a “low” corrosion rate. This gives an inspection type of “Type A” for the corrosion mapping.

For the cracking mechanisms, the CRA predicted a “Low likelihood”. By their nature, stress corrosion and wet H_2S cracking mechanisms principally occur in regions of highest stress, and thus the location is “Likelihood – clearly defined”. Cracking can proceed rapidly, impacting on vessel integrity within its planned life, thus “High rate” is chosen. This gives and inspection “Type B” for the weld inspections.

Determination of Inspection Interval

A total of thirty two scan areas were inspected on the shell of the Vent Knock Out Drum. However, the bottom head could not be mapped due to the curvature of the head and restricted access. A manual inspection of this region was carried out and pitting to 2 mm deep was reported.

In this case it is considered that the inspection actually carried out would have a broadly similar capability to identify degradation as the automated procedure originally defined, and therefore the inspection interval does not need to be modified in the light of the change in method. The flaws identified, the 2mm deep pitting, should be evaluated using company procedures and other appropriate codes such as API 579 [9]. In this case, the flaws were within acceptable limits and no further action was required. Therefore, the inspection interval could be safely maintained at 3 years.

7.4.4 HP Condensate Separator

Background information

Inspection History

There is no evidence service induced degradation.

Expected degradation

The vessel is constructed in carbon steel overlaid with roll clad 316 stainless steel.

The nominal operating temperature is moderate (19°C).

The vessel is not insulated.

Degradation of the stainless steel cladding is unlikely in the process conditions (the threshold temperature for chloride pitting/SCC (approx 200°C) is significantly higher than the operating temperature. Breakdown of the cladding would lead to exposure of the underlying carbon steel to the process conditions and corrosion would then be expected. This is low likelihood but the inspection should seek to demonstrate that the cladding remains intact.

NII Inspection Plan

Following the HOIS decision guidance procedure, it was concluded that the vessel was suitable for inspection by NII using a method with medium efficiency primarily to confirm integrity of the lining, although degradation is considered to be negligible if the lining remains intact. Credible damage mechanisms include:

- corrosion – some internal corrosion may be present. If so, it is anticipated at the liquid level and would be expected to be more advanced at the inlet end of the vessel. No particular susceptibility for corrosion of nozzles (except inlet nozzle) or welds in preference to parent material
- stress corrosion cracking and Wet H_2S cracking identified as low probability in CRA.

The proposed NII work-scope was therefore as follows:

- UT corrosion mapping of the vessel shell and wall thickness measurement to repeat base-line survey.
- Manual UT inspection of accessible areas of shell long/circ. welds for cracking at the internal surface.

Inspection Evaluation

1) corrosion mapping (standard resolution) and manual UT for signs of pitting and SCC of 4 bands centred on the bottom of the vessel and covering the lower 30 degrees of circumference
2) corrosion mapping (standard resolution) and manual UT of bands approximately 300 mm wide covering the lower portion of both sides of the vessel to approximately 300 mm above the vessel centreline. The bands should extend from the weir position to approximately 300 mm upstream of the weir (i.e. towards C2)
3) corrosion mapping (standard resolution) and manual UT of regions extending approximately 300 mm longitudinally and 600 mm circumferentially at the top of Strakes 1, 2 and 3. Each region should be located lengthwise approximately centrally on the strake
4) circ. welds C1 and C2 to be inspected 50% by 45 degree manual UT and TOFD. Must include regions at bottom, mid-side and top of vessel
5) the bore of nozzles N1, N2, N3, N4, N5A, K1C, K2C, K4B, K3B, A1A and A1B to be inspected for signs of pitting / SCC using ultrasonic scanning at each of the four cardinal positions.
Inspection Evaluation

Determination of Inspection Type

The inspection type is determined separately for the two degradation methods considered, internal corrosion and cracking, using the flowchart in Figure 3-2.

As the CRA identified no corrosion mechanisms leading to a high probability of degradation, the flow chart is entered at the “Low likelihood” spine. Corrosion is generally either “General” or “Localised” in extent. In order to present a conservative assessment, in this case “Localised” has been assumed. The corrosion rate is taken as “low” given the results of the CRA, which gives an inspection type of “Type A” for the corrosion mapping.

For the cracking mechanisms, the CRA predicted a “Low likelihood”. By their nature, stress corrosion and wet H2S cracking mechanisms principally occur in regions of highest stress, and thus the location is “Likelihood – clearly defined”. Cracking can proceed rapidly, impacting on vessel integrity within its planned life, thus “High rate” is chosen. This gives and inspection “Type B” for the TOFD inspection.

Determination of Inspection Interval

For reasons of accessibility, one area at the top of the separator vessel was not able to be inspected according to the original inspection plan. Following the flowchart in Figure 3-2, the inspection was carried out using the correct methods and procedures, thus the quality factor is taken as 1, however the coverage factor needs to be determined using Figure 4-3.

The un-inspected region is expected to experience similar conditions to the other two top surface areas which were correctly inspected, although the top surface is not considered to be an area of particular concern. None of the scans carried out on the vessel identified any areas of concern.

The coverage factor is calculated using the flowchart (Figure 4-3). As the top surface is not considered to be of particular concern, the area of missed inspection is compared to the total area inspected for the vessel. In this case <10% of the total planned inspection. The coverage factor is therefore determined as 1 and no reduction in inspection interval is required.

Had the top surface been considered to be a high risk area, however, then the missed area would have been determined against the total equivalent area. In this case one out of three equivalent areas designated for inspection at the top of the vessel was not inspected, therefore approximately 33% of the intended coverage was missed. The coverage factor for this case is determined to be 0.5 (an area of concern, but with similar features having been inspected and <50% missed). Further inspection is therefore recommended at a reduced interval in order to maintain safety levels.

This case therefore illustrates the importance of engineering judgement in the evaluation process. Clearly differing conclusions can be drawn through different interpretation of the results. It is therefore important that the supervising inspection engineer records all stages of the evaluation process for auditing purposes and future reference.
8. References

1) EN 473 General Principles for Qualification and Certification of NDT personnel.
2) ISO 9712 Non-destructive testing - Qualification and certification of personnel.
12) DNV-RP-G101 "Risk Based Inspection of Offshore Topside Static Mechanical Equipment".
21) "Best Practice for the Procurement and Conduct of Non-Destructive Testing Part 1: Magnetic Particle and Dye Penetrant Inspection", HSE, April 2002.
23) Discussion with P Horrocks regarding AEA Technology RBI principles, January 2001
APPENDIX A
REVIEW OF NON INTRUSIVE NDT METHODS

A.1 Introduction
This review gives a brief description of the principles, capabilities and limitations of NDT methods which might be considered as non-invasive inspection methods, including:

1) Ultrasonic Testing
2) Eddy Current Testing
3) Liquid Penetrant
4) Magnetic Particle Inspection
5) Magnetic Flux Leakage
6) Thermography
7) Radiography
8) Backscatter or Compton Imaging
9) Acoustic Emission
10) Remote Visual Inspection
11) Shearography.

A.2 Ultrasonic Testing

A.2.1 Conventional Ultrasonic Testing
Conventional ultrasonic testing is based on the generation of ultrasonic beams by means of probes containing a piezoelectric element excited by an electrical pulse. The piezoelectric element vibrates and generates mechanical waves of frequency typically in the range 1 MHz – 10 MHz. The sound wave propagates into the specimen and discontinuities make the waves reflect back to the same or to a different transducer.

Conventional ultrasonic transducers can generate a variety of angle beams which can provide sufficient coverage for the inspection of the whole thickness of a specimen.

Ultrasonic inspection can be used for the monitoring of corrosion by measuring the wall-thickness of the specimen. It can also detect and size pits.

A poor surface finish, thick paint or inspection at high or low temperature may cause problems for ultrasonics (although more appropriate transducers can be used for particular condition, e.g. specially designed high temperature transducers can be used to inspect hot surfaces).

A.2.2 Ultrasonic Imaging
Ultrasonic imaging systems can be used to improve reliability in detecting and/or sizing flaws.

A.2.2.1 Automated Ultrasonic Imaging
Ultrasonic imaging systems integrate microprocessor technology with non-destructive testing methods and can perform inspections on vessels and piping from the external surface. Wall thickness up to 600 mm can be inspected for both fabrication and service induced cracking, wall thinning or clad delamination in a single pass. The full RF waveforms are collected and reliable repeatability is achieved. Multiple testing allows analysis to be performed while the inspection is carried out.

Applications include erosion/corrosion detection and monitoring, fatigue crack detection and sizing, hydrogen blistering and stepwise cracking and stress oriented hydrogen induced cracking.

A.2.2.2 Ultrasonic Thickness (Corrosion) Mapping
In ultrasonic wall thickness mapping systems, a transducer is linked to a computer so that thickness data for each predetermined measurement position can be recorded. The transducer is scanned manually over the surface and the thickness readings are stored on disk. After the scanning is finished, the data are plotted in a wall thickness map. Each thickness level can be colour coded and wall thinning by corrosion or erosion is more readily recognised than by manual inspection. High reproducibility (typically within 0.3 mm wall loss) enables accurate monitoring and calculation of corrosion rates.

Wall thickness mapping can be applied in-service at temperatures up to about 250°C using special high temperature probes and couplant. Wall thinning, pitting corrosion, flow acceleration corrosion hydrogen induced corrosion and hot hydrogen attack can be detected and imaged.

Recently there have been significant advances in the technology used for corrosion mapping, which has greatly increased scan speeds and reduced noise levels, allowing more reliable detection of small pitting type flaws. These systems are based on high speed automated scanning systems (crawlers etc.), which are well suited to scanning large, unobstructed areas such as sections of vessel shells between nozzles etc.

For NII of vessels, corrosion mapping is a widely used method for detection and sizing of internal corrosion/erosion flaws (both localised and generalised loss of wall).

A.2.3 Time of Flight Diffraction (TOFD)
TOFD (Time of Flight Diffraction) is an advanced ultrasonic inspection method which can simultaneously detect and size indications. TOFD sizing in the through wall direction is based on the measurement of signal arrival times which is inherently more accurate than methods based on amplitude. With TOFD, through wall sizing accuracy is typically 1 mm or better.

It provides reproducible fingerprints which makes it suitable for condition monitoring. Initial manufacturing flaws can be monitored and service induced flaws detected and progressively monitored. TOFD examination only requires external access to the object to be inspected. TOFD can be applied on hot structure up to 200°C using special transducers. Weld inspection of heavy wall pressure vessels (up to 300 mm wall thickness) has been carried out. Nozzle and flange welds (complex geometry) can be inspected with prior computer simulation modelling to aid inspection planning and result evaluation.

For NII applications, TOFD is often used for inspection of welds for typical welding flaws, including weld root erosion/corrosion, cracks, lack of fusion etc. Recently, there have also been NII applications where TOFD has been used as a rapid scanning method for detection and sizing of backwall pitting type wall loss flaws, as an alternative to more conventional corrosion mapping.

A.2.4 Creeping Head Inspection (CHIME)
The CHIME method (Creeping Head Wave Inspection Method) consists of the transmission of an ultrasonic signal between two probes that are placed a distance apart (up to one metre) scanning a parallel (or near parallel) surface.

The transmitter fires a pulse of ultrasound that gives rise to creeping waves propagating along both the surfaces, and critical angle head waves (shear waves) are generated at all parts between the surfaces. As a result, the full wall volume between the probes is covered. The coverage is achieved with little attenuation, allowing the transmitting and receiving probes to be well separated compared to traditional inspection.

Wall thickness up to 40mm at a standard operational frequency of c. 2 MHz and inspection widths (distance between the two probes) of up to one metre have been established. The CHIME scans can provide information about thickness of the sample.
(by measuring the time interval between successive peaks) or about any flaw which locally changes the thickness.

Flaws due to corrosion or cracking, reduce the CHIME signal magnitude and can change the arrival times of the signal peaks independent of their location between the transmitter and receiver.

The method has tolerance to in-service surface conditions and most coatings. It is sensitive to the presence of corrosion on internal and external surfaces and provides an estimation of the extent of the corrosion area and nominal wall thickness in areas between corrosion. Some approximate information on the through-wall extent of a flaw is also obtained, by the amount of the CHIME signal loss produced.

CHIME has been tested on samples containing general and isolated corrosion, stress corrosion cracking, hydrogen and has demonstrated tolerance to surface conditions such as general roughness or thin layers of coating.

For NII applications, CHIME is most often applied to sections of components made inaccessible to conventional ultrasonic methods by geometry, such as pipe supports and pipe clamps. The method also has potential for fast screening for corrosion pits over large areas of vessel shells.

A.2.5 M-Skip

M-skip method is a new ‘medium’ range pitch-catch ultrasonic inspection technique developed within the HOIS programme since 2005. The method has some similarities to CHIME, but provides more quantitative information on wall thickness and wall loss via analysis of the arrival times of signals.

M-skip is a variant of the well known TOFD method but is based on angled shear wave probes, separated by the distances required to inspect wider pipe supports and clamps. The signals travelling between the probes then typically experience many reflections, or skips, between the front and back component surfaces.

Measurements of the arrival times of the different skip signals can be used to determine the average wall thickness between the probes. For areas of wall loss on either the front-wall or back-wall surfaces, the signal arrival times which involve reflection/scattering of the defect will be reduced. Measurements of the differences in the arrival times between the wall-loss signals and the skip signals allows the maximum depth of wall loss to be derived, assuming the number of reflections from the area of wall loss is known. If this number of reflections is unknown, the assumption of a single defect reflection provides a conservative estimate of the actual depth of the wall loss.

To date, M-skip has been applied to carbon steel plates and pipes with wall thicknesses in the range 7 to about 35 mm, with probe separations up to at least one metre. Typical probe frequencies are 3-5 MHz.

M-skip has been applied to carbon steel components containing generalised and isolated corrosion. For NII, M-skip is applicable to sections of components made inaccessible to conventional ultrasonic methods by geometry, such as pipe supports and pipe clamps. The method also has potential for fast screening for corrosion pits over large areas of vessel shells or long lengths of pipework.

A.2.6 Long Range Ultrasonics

A.2.6.1 LORUS

The principle of the method consists of a high sensitivity angle beam probe used in multi-skip mode to completely flood the wall of the component being inspected. Any changes of the thickness of the pipe at the outer or inner surface can result in reflection of some of the ultrasound back to the transducer. Ranges of over a metre can be achieved. The amplitude of the response provides an indication of severity although it is not possible to measure accurately the through wall dimension of corrosion, or determine whether it is at the inner or outer surface. The surface should be free of impurities and loose deposits to provide sufficient acoustic coupling at the transducer test point. The method is used to detect corrosion at locations with limited access, such as: insulated and (with certain restrictions) clamped pipes, annular plates in storage tanks or under reinforcement plates. The interpretation of the output signals is of prime importance as the signals which reach the transducer include those from welds, supports and other geometrical features and would superimposed over the signals from corrosion area.

“LORUS” (LOng Range UltraSonics) was developed by RTD. Inspection results are reported in high-resolution colour maps (presented in 3D views: top, side and end images) and corroded areas are listed by angular position and extent with a position accuracy of ±10mm. The LORUS system can be applied to components in the thickness range 6-25 mm. Well-bonded paint coating is acceptable. Heavy corrosion may obscure detection of corrosion at larger distances from the probe in the plate.

Trials have been performed to investigate the capability of LORUS to detect corrosion inside a vessel underneath a nozzle reinforcing plate (which prevents detection using conventional 0° ultrasonic inspection). The trials were performed using two test-pieces manufactured by MBEL. One test-piece was a nozzle welded into a square plate (representing the vessel) and containing a 90 mm wide (radial extent) reinforcing plate. The test-piece contained eleven simulated corrosion sites at various locations under the reinforcing plate. The other test-piece was simplified geometry manufactured from flat plate and containing four simulated corrosion sites. All fifteen simulated corrosion sites were detected.

A.2.6.2 Lamb/Guided Wave Methods

Lamb waves are “guided” or “plate” waves which can exist in plates or pipes where the thickness is the same order of magnitude as the ultrasound wavelength. The wave motion couples both surfaces of the plate together, such that the plate or pipe acts as an acoustic waveguide, allowing the propagation of a series of different Lamb-wave modes, whose velocities depend on the plate thickness and wavelength.

This method is generally applied using a ring of probes which are clamped around the outside of a pipe. The method is pulse-echo and the transducer array is configured such that the test may be carried out in one direction along the pipe and then in the other. Long lengths (ca. 30 m - 50 m or more) of pipe may be examined in both directions from a single test point, although certain pipe coatings (especially soft coatings such as bitumen or tape wrap) can severely attenuate the Lamb waves, and hence reduce the effective range of the method.

Wall loss flaws are detected by the reflected waves they generate. For reliable detection, a wall loss flaw needs to reduce the cross sectional area of the pipe by around 2-5% (this varies depending on equipment used and general conditions of the pipe to be tested). The amplitude of the received flaw echo provides some information on the overall flaw extent, but not on the maximum wall loss.

The detection capabilities at locations close to (or within) pipe features (e.g. under simple supports) depend on the equipment used and the operator skills. In some case detection capabilities are hindered by the presence of pipe features and the user shall refer to the manufacturers’ recommendation.

For NII applications, Lamb/Guided inspection is generally used as a fast screening method for the inspection of long lengths of straight pipework, although recent advances allow some inspection around bends. Guided wave techniques have been used to rapidly inspect insulated and clad pipeline corrosion, and the results correlated well with subsequent investigations.
Lamb waves can also be generated in flat or large curvature plates, but these methods are much more developmental than the systems for pipe inspection. Other developments have been used for permanent monitoring of pipes in hazardous areas, and for inspection of heat exchanger or boiler tubes.

**A.2.7 Electromagnetic Acoustic Transmission (EMATs)**

Electromagnetic acoustic transducers (EMATs) are a relatively new method for generating and receiving ultrasound which offer certain advantages compared to conventional (piezoelectric) probes. However they have much lower sensitivity than conventional probes and are much more expensive.

An EMAT consists of a flat pancake coil of wire carrying a radio frequency current and a magnet which produces a steady magnetic field. The radio frequency current induces eddy currents in the surface of the specimen and their interaction with the magnetic field results in Lorentz forces or magnetic forces (predominantly magnetostrictive) which cause the specimen surface to vibrate in accordance with the applied radio frequency current. The ultrasonic waves which have been generated at the specimen surface propagate into the specimen in the normal way. They can be detected after reflection from a flaw, for example, by the same transducer or by a separate one using a magnetostrictive effect. Depending on the direction of the magnetic field the EMAT can generate shear (radially, horizontally or vertically polarised), compression or Rayleigh waves.

EMAT ultrasonic can be a non-contact method since there is no need of fluid couplant and it can be used on rough, scaled or painted surfaces, although any lift-off from the specimen surface reduces the sensitivity still further.

EMAT probes are now available from certain large probe manufacturers for use with conventional manual flaw detectors. However these are intended for a special application, involving thickness gauging of carbon steel components with a magnetite layer which has formed through operation at high temperatures. The presence of this magnetite layer greatly enhances the efficiency of ultrasound generation and detection, via the magnetostrictive effect. For all other steel components, without this coating, EMATs remain a research method only.

EMATs can operate on hot metals, since EMATs are relatively easy to keep below 100°C with simple water cooling. They can be used up to 700°C if they are brought into momentary contact with the sample and up to 460°C in constant contact. Thicknesses from 2 mm up to 150 mm or higher can be inspected. EMATs can be used to measure wall thickness at high temperature with an accuracy of ±0.5 mm. EMATs can also be used on low temperature surfaces (down to liquid nitrogen temperature).

However, when the EMAT is used as a transmitter, problems emerge due to low sensitivity. One recent method used to solve this problem is to use a laser to generate ultrasonic waves and an EMAT as receiver; the EMAT-LASER or EMAT-EMAT method is of high cost compared to more traditional methods, but has proved to be effective for certain specific applications.

EMATs have been used to measure the wall thickness of steel galvanising bottles at their normal operating temperatures that are in excess of 450°C. The kettles are typically fabricated from 50 mm thick steel. The study indicates that it is possible to measure the steel wall thickness to within ±0.5 mm.

EMATs are not typically currently widely applied for NII applications.

**A.3 Eddy Current Testing**

Eddy current testing is based on inducing electrical currents in the material being inspected and observing the interaction between these currents and the material.

Conventional eddy current testing methods are not suitable for volumetric inspection of vessels since typical penetration depth of the eddy currents is less than 1 mm for ferritic material and several millimetres for austenitic material. Advanced eddy current methods can significantly increase penetration depth as described below.

**A.3.1 Pulsed Eddy Current Testing**

In the pulsed eddy current method, a coil is supplied with a short pulse. The resulting eddy current pulse propagates in the specimen as a heavily attenuated wave of electromagnetic energy with a phase velocity depending on the material and the frequency. For material thickness measurement, a detection coil can be placed close to the transmitter with suitable shielding. Because the wave propagation is highly dispersive, changes in pulse shape occur with distance into the specimen and by measuring the time-amplitude characteristics of the received pulse and comparing them with the time of occurrence of certain signal features from similar calibration tests via a computer, flaw depth can be determined. A change in wall thickness indicates the presence of corrosion or erosion. The probe does not need to be in contact with the component and can therefore be applied through insulation, and also thick coatings or layers of deposit as long as they are non-conductive and non-magnetic.

This method can be used for in-service inspection, has good repeatability (±0.1 mm), is transportable and robust, operates over a wide range of climatic conditions, can be applied on components with temperatures of -100°C to +500°C (above these temperatures, the use of the system is prohibited due to the reduction of magnetic permeability), measures through any non-conductive and non-magnetic material up to 100 mm thickness (in favourable circumstances even up to 150 mm). Ferritic cladding up to a certain thickness (at present 0.8 mm) does not influence accuracy and the transducer can be up to 30 metres from the base unit.

However, typical equipment is limited to inspection of wall thicknesses below 40 mm and pipe diameters over 100 mm, it only detects general corrosion or erosion over relatively large areas, does not detect small isolated pits and can be influenced by the presence of large metal masses nearby.

**A.3.2 Saturated Low Frequency Eddy Current (SLOFEC)**

This method is based on the eddy current method with DC magnetisation. A magnetising yoke containing an electromagnetic is used to generate a strong magnetic field in the material under test. An eddy current probe senses component metal loss due to the local concentration of the magnetic field.

If the coil is used in differential mode then localised wall loss such as pitting can be detected. General wall thinning can be measured by using the system in absolute mode.

A saturated low frequency eddy current ("SLOFEC") system has been developed by a German company (Kontroll Technik). SLOFEC can provide an improved performance for some applications where classic magnetic flux leakage (MFL) is used, e.g. the inspection of tank floors and pipe inspection.

Two major advantages of SLOFEC compared to classic magnetic flux leakage are that the maximum wall thickness which can be inspected is around 30-35 mm, compared to around 10-15 mm for MFL. Recent studies also suggest that SLOFEC has improved sensitivity to small pitting flaws than MFL. The data from SLOFEC is stored in digital form, and analysis of the signal characteristics provides information on the location of wall loss flaws (backwall/ frontwall). Some information on the extent of an indications wall loss is available, but this is less quantitative than that provided by a method such ultrasonic corrosion mapping.

For NII, SLOFEC has considerable potential for the rapid detection/screening of corrosion in vessel shells and pipework.

**A.4 Liquid Penetrant Inspection**

Liquid penetrant techniques, including dye and magnetic par-
ticle variations are low cost methods and are easy to apply and used to detect surface breaking flaws such as cracks, laps and porosity. Large areas can be inspected but liquid penetrant is a slow process in terms of application and flaw indication.

The principle of liquid penetrant method: first, the surfaces to be tested are cleaned – pre-cleaned to remove scale etc., degreased and dried. The chosen penetrant (solutions of coloured or fluorescent dyes in oil-based liquids) is applied to the surface of the specimen and allowed time to soak into discontinuities. The excess penetrant is removed (by water, solvent, water and detergent or by emulsifier). A developer is then applied. After a period of time and if a discontinuity is present, the penetrant seeps out the developer at the discontinuity position, causing a marked local reduction in developer contrast.

The sensitivity of penetrant inspection process can be very high and it is possible to detect very small cracks having opening widths of about 1 μm.

Liquid Penetrant inspection is only applicable to the accessible component surface, and is not therefore an NII method.

A.5 Magnetic Particle Inspection

Magnetic particle inspection (MPI) is used for the detection of surface and near-surface flaws in ferromagnetic materials. It is one of the most extensively used electromagnetic methods in industry as it is easy to apply and provides a direct visual indication of surface breaking crack.

The method involves the magnetisation of the component either locally or overall, by application of a permanent magnet, electromagnet or electric current. A magnetic field is produced inside the material. The magnetic field becomes distorted by the presence of a flaw causing a local magnetic flux leakage.

Ferromagnetic particles in the form of dry powder or suspended in a liquid (daylight visible or UV fluorescent particles) are sprayed onto the surface of the specimen to reveal the leakage field. The particles are attracted by the magnetic field and accumulate in the vicinity of the flaw, which is subsequently made visible.

The minimum angle between the magnetic field and the detection of imperfection is 30°. The optimum sensitivity is reached when the magnetic field is perpendicular to the imperfection orientation. Therefore, the flaws must lie between 30° and 90° to the magnetic field in order to be detected. The magnetic field is therefore applied in two directions at right angles to each other.

MPI inspection is only applicable to the accessible component surface, and is not therefore an NII method.

A.6 Magnetic Flux Leakage

The component is locally magnetised and depending upon the level of induced flux density, magnetic flux leakage due to both near and far surface flaws is detected by the voltage induced in a detector coil or a Hall-effect element which is traversed over the surface of the specimen. The method is not limited to surface-breaking or near-surface flaws, although it becomes increasingly sensitive to far-surface flaws with increasing levels of magnetisation. Also, the output from the detector can be amplified, filtered, digitised, etc., and stored to produce automated inspection systems. Multi-element and differential probes can be used, and inspection speeds can be very high.

The method is finding increasing use in the petrochemical industries for providing high-speed inspections of storage tank floors, as well as carbon steel pipes. These systems utilise either permanent or electromagnets to provide localised near-magnetic saturation coupled with induction-coil or Hall Effect sensor arrays for detecting anomalous flux leakage caused by the presence of corrosion flaws (both near and far surface).

Many of these systems rely upon the use of an adjustable threshold or amplitude gate to provide the detection of corrosion in real-time, while some of the more advanced systems, through the use of both advanced electronics and signal processing, are able to provide corrosion-maps of inspected areas similar to the C-scan representation of ultrasonic data.

Maximum wall thickness which can be inspected is around 10-15 mm, and some information is provided on the extent of the wall loss, but MFL is less quantitative than methods such as ultrasonic corrosion mapping.

MFL can be used for NII, and crawlers have been developed for inspection of vertical walls, as well as the more conventional floor scanners.

A.7 Thermography

Thermography is based on the measurement of the heat distribution across a surface. The effect of flaws on thermal conductivity and emissivity of test materials can be analysed by a thermographic method.

Passive thermography investigates the heat distribution of a structure with a special infrared camera and looks for hot spots, which could for example be due to loss of wall flaws in a vessel pipe containing hot products, or a breakdown in thermal insulation.

An alternative method, known as transient or pulsed thermography involves inducing a heat pulse into a component by suddenly raising the temperature of the component surface locally, using an external heat source (e.g. flash tube). Within the HOIS programme, an alternative heat source, using induction heating was developed to allow the more effective inspection of thicker steel components.

The heat pulse will diffuse into the material. The rate at which the heat front is subsequently dissipated depends on the structure and flaw content below the surface. The surface temperature of the structure is monitored using an infrared camera.

Anomalies in the temperature distribution reveal the presence of flaws or local changes in thermal conductivity due to e.g. breakdown in insulation. The method is made more convenient by using a video recorder or computer to store the rapidly changing temperature pattern after the structure surface is heated. Then, flaws in conducting materials that have only a transient effect on the temperature distribution may be detected. Quantification of anomaly size is more usually accomplished by application of a second non-destructive evaluation method as thermography can estimate size only on thin outer layers.

A new method known as lock-in thermography is reported to be much quicker, more accurate and be able to probe deeper than conventional thermographic inspection methods. Lock-in thermography is a method which uses a modulated source to energise the material under test. However, this method is still limited for detection of flaws of several millimetres below a material surface. To date, tests have been carried out at frequencies which allowed depth ranges of 10 mm to be covered.

Transient thermography can be used as a rapid, non contacting method for detection of sub-surface flaws or voids. However, it becomes less effective in detection of sub-surface flaws as the depth of the flaw increases. Typically for detection, the width of a flaw must be greater than its depth below the inspection surface. Laboratory tests of the induction heater developed in the HOIS programme showed detection of flaws (diameters 15-30 mm) at depths of 10 mm below the inspection surface. Smaller diameter flaws could be detected at smaller depths.

A.8 Radiography

Radiographic inspection is a process of testing materials using penetrating radiation - either electromagnetic radiation of very short wavelength (X-rays, gamma-rays), or particulate radiation (neutron radiation). Radiography is based on the differen-


A.9 Backscatter (Compton’s) Imaging

Compton scattering tomography is a relatively new method for industrial non-destructive testing, making use of \(\gamma\) or X-ray photons scattered inside the component under examination. The source emits a finely collimated beam into the material and a finely collimated detector allows measurement of the number of photons that are scattered. The detected signal is largely composed of singly scattered photons from the volume defined by the intersection of the incident beam and the acceptance solid angle of the detection collimator. The amount of scattered radiation produced is directly related to the electron density of the material, which corresponds well to the physical density of the material. The major advantage offered by backscatter imaging is that it can be implemented from one side of the object.

It can provide information even if the object is very massive, or does not permit X-ray transmission through it, or does not permit access to the opposite side. The measurement can be performed in the presence of protective coatings and because the source and the detector are placed on the same side of the test-piece, large components filled (with oil for example) can be inspected at speeds much greater than can be done with conventional through-transmission radiography. Compton backscatter imaging is a non contact method and can therefore be applicable at elevated temperatures.

In Compton scatter imaging a three-dimensional image is built up point by point. The time necessary to obtain an image of a particular volume of interest in the object under study is a function of the size of this volume. The scanning rate varies inversely with the square of the inspection volume. If larger voids are of interest, greater scanning rates are possible and therefore shorter scanning times can be used although there is loss of spatial resolution. A detector array is usually used to cover the entire thickness of specimen traversed by the source beam, for each position of the source. A feasibility study on the use of Compton backscatter gamma-ray tomography for underwater inspections offshore shows that the use of 10 Ci of \(^{60}\text{Co}\) should provide a scanning rate of about 35 cm\(^2\)min\(^{-1}\). The study showed that this method is capable of detecting 5mm cubical flaws positioned at a depth of 32 mm of steel. Therefore, this method could be an attractive tool to detect corrosion/erosion of the inner surface of vessels. However, this is an expensive method and it might need to be adapted for particular applications.

The major drawbacks of Compton scatter imaging systems has been their high capital costs and very slow scan speeds, which have precluded their application to all but the highest value components.

There have been however some recent developments to this method, especially in the USA, and systems are now being used for certain specialised large area scanning applications (e.g. foam thermal insulation on NASA’s Space Shuttle). This is not currently a recognised NII method in the oil and gas industry, but there may be some potential for applications such as CUI inspection.

A.10 Acoustic Emission (AE)

Acoustic emissions are pulses of elastic strain energy released spontaneously during deformation of materials. When a body suddenly deforms locally and relieves local stresses, a burst of energy is emitted. AE can be released by a number of causes such as plastic deformation, inclusion cracking, crack growth, but also by corrosion, phases changes and impact. External factors such as mechanical impacts, friction, machinery vibration, welding operations, can also produce acoustic emission.

These emissions propagate through the specimen and are detected by sensors placed on the surface of the specimen, which in turn convert the energy into electrical signals. These
are amplified, stored, processed and displayed. Acoustic emission examination is non-directional as AE propagates in spherical wave fronts. Therefore, a sensor located anywhere in the vicinity of an acoustic emission source can detect the resulting acoustic emission. A large volume of a structure can be monitored at once; it is not necessary to examine specific regions. Since only limited access is required, “active” discontinuities in areas inaccessible to the more traditional non-destructive methods can be detected. Location of the source of the acoustic emission can be accomplished by several search units positioned over the surface area to be tested and monitoring the time of arrival of the signals to the various search-unit locations. Because of the high velocity of sound and the relatively close spacing of search units on a steel vessel, time resolutions must be made in microseconds to locate the source within a centimetre. In most cases, inspection requirements are such that data must be available in a short period of time. Therefore most systems of this type utilise a computer for handling and displaying the data.

The in-service inspection of a pressure vessel may consist of monitoring during periodic proof testing, during normal pressure surges, and during other operational procedures. When the vessel is pressurised to a level less than that to which it has been previously subjected, little or no acoustic emission occurs. Therefore, on subsequent pressurisations no AE will be generated unless a crack has extended in service because of corrosion or fatigue. On pressurising after crack growth, the stress system at the enlarged crack will be changed from that previously, and further emission will be obtained. The detection of in-service stress corrosion cracking is reported to be a relatively straightforward application as stress corrosion cracking produces copious AE. However, the success depends on the particular material tested. Some materials are quiet almost up to the point of failure. Slow, continuous crack growth mechanisms such as active path corrosion are not detectable in themselves, but if general yielding has not occurred, they may be detectable through associated plastic zone growth.

The main advantages of the method are that it allows large area coverage, growing discontinuities can be detected, location of discontinuities is possible, inaccessible area inspection, online application (even at high temperature) and non-invasive. However, not all discontinuities emit detectable acoustic emission, loading methods must be analysed to ensure they promote detectable crack growth, many factors can obscure acoustic emission (geometry, materials, construction, noise), discontinuity size not determinable and special sensors have to be used at high temperature (high temperature sensors are available to operate up to 260°C).

A.11 Remote Visual Inspection

Remote visual inspection using equipment such as boro-scopes, fibre optic boro-scopes and video-scopes is a very useful tool which can give information on the condition of pipes, turbines, heat exchangers, and other critical machinery without costly and time consuming disassembly. A boro-scope is a long, tubular optical device that illuminates and allows the inspection of surfaces inside narrow tubes or difficult to reach chambers.

Rigid boro-scopes are generally limited to applications with a straight-line path between the observer and the area to be observed – an orbital scan allows the user to view flaws in a 360 degrees arc. The lengths and diameters of the probes can be tailored for optimum results. Typical sizes range in length from 0.15 m up to 30 m and in diameters from 0.9 to 70 mm. Magnification is usually 3 to 4 times although magnifications up to 50 times are available.

Flexible boro-scopes are used when there is no straight pas sageway to the point of observation. There are two types of flexible boro-scope which are flexible fibre-scopes and video-scopes with a CCD image sensor at the end. The flexible fibre-optic boro-scope carries visual information through fibre-optic cables each of which makes up a picture element of the final image. Articulation controls allow the user to manipulate the end of the scope in the interior of the structure. Special protective coatings allow the boro-scope to operate while submerged in liquid. They are typically available in diameters from 1.4 to 13 mm and in lengths up to 12 m.

Rigid and flexible boro-scopes are available in a wide variety of standard and customised designs and several factors can influence the selection of a scope for a particular application. These factors include focusing, illumination, magnification, working length, direction of view and environment.

Both types of boro-scopes can be manufactured to withstand a variety of environments. Rigid endo-scopes as standard will accept temperatures from -30°C up to 150°C and will withstand pressure up to 6 bars. Flexible endo-scopes will work in temperatures up to 80°C and will withstand pressures of between 2 and 3 bars. Boro-scopes can be tailor made to meet different specifications such as length (up to 18 m), diameter (down to 10 mm), lighting system and the use of a jacket protection to allow the system to be used at higher temperature (up to 1600°C). However, the price of the system is related to these options and would increase rapidly with the quality of performance.

Boro-scopes provide a means of checking in-service flaws in a variety of equipment and are of particular interest for the build-up of corrosion and scale on the internal surfaces of for example heat exchangers.

Video-scopes are similar to fibre-optic boro-scopes. The video-scope involves the electronic transmission of colour or black and white images to a video monitor. The advantage of these devices is their length. Due to light attenuation fibre-optic boro-scopes are limited in length, but some video-scopes can travel as far as 30 m to the inspection site. Other advantages of the video-scope compared to the fibre-optic boro-scope are that the display can help reduce eye fatigue, there is no honycomb pattern on irregular picture distortion and the electronic form of the image signal allows digital image enhancement and the potential for integration with automatic inspection systems. It produces generally higher resolution.

Video cameras are more sensitive to temperature and will only generally work at temperatures from 0°C to 45°C.

A.12 Shearography

Shearography is a promising relatively new NDT method. It is a non-contact laser based interferometry system that is used to detect areas of stress concentration caused by anomalies in materials. The method senses out-of-plane surface displacement of an object in response to an applied load. An laser beam is used to coherently illuminate the test sample. The light reflected from the test sample is collected by a photo lens and imaged through an image shearing interferometer onto the sensor array of a CCD video camera. The image shearing interferometer produces a double image on the CCD array. The second image is offset from the first one. The interferogram recorded by the CCD camera is thus indicative of motion toward the camera over an interval of the image shearing distance in the plane of the test sample surface, or the relative slope of the test sample surface. Data are represented in the form of a fringe pattern produced by comparing two states of the test sample, one before and the other after a load is applied.

Shearography can be applied to a variety of materials, including steel, aluminium, plastic and composite. Shearography is a remote, non-destructive, non-contact and very fast method.

It can perform measurements in hazardous conditions such as high temperature, plasma and nuclear radiation. Laser Shearography is very sensitive to slight changes in surface stain due to sub-surface flaws. It can map changes in strains to 0.1 microstrain at video frame rates. However, Shearography is not currently used as an NII method within the oil and gas industry.
### A.13 Inspection Method Capabilities

<table>
<thead>
<tr>
<th>Flaw type</th>
<th>Inspection method</th>
<th>Inspection efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Detection</td>
</tr>
<tr>
<td>General wall thickness loss</td>
<td>UT Pulse-echo 0 deg. compression wave</td>
<td>H</td>
</tr>
<tr>
<td></td>
<td>UT mapping (C-Scan)</td>
<td>H</td>
</tr>
<tr>
<td></td>
<td>UT EMAT</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td>Phased Array</td>
<td>H</td>
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<tr>
<td></td>
<td>M-Skip</td>
<td>H</td>
</tr>
<tr>
<td></td>
<td>Pulsed Eddy Current</td>
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<tr>
<td></td>
<td>Film Radiography</td>
<td>M</td>
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<tr>
<td></td>
<td>Computed Radiography (tangential on pipes)</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td>Magnetic Flux Leakage</td>
<td>L</td>
</tr>
<tr>
<td></td>
<td>Saturated Low Frequency Eddy Current</td>
<td>L</td>
</tr>
<tr>
<td>Local wall thickness loss, pitting</td>
<td>UT Pulse-echo 0 deg. compression wave</td>
<td>H</td>
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<tr>
<td></td>
<td>UT mapping (C-Scan)</td>
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<td></td>
<td>Phased Array</td>
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<tr>
<td></td>
<td>M-Skip</td>
<td>H</td>
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<tr>
<td></td>
<td>Film Radiography</td>
<td>H</td>
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<tr>
<td></td>
<td>Compton Backscatter</td>
<td>H</td>
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<tr>
<td></td>
<td>Computed Radiography (double wall with computerised analysis of image grey levels)</td>
<td>H</td>
</tr>
<tr>
<td></td>
<td>Magnetic Flux Leakage</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td>UT CHIME</td>
<td>H</td>
</tr>
<tr>
<td></td>
<td>Pulsed Thermography</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td>UT Long Range (Lamb Wave)</td>
<td>M</td>
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<tr>
<td></td>
<td>Shearography</td>
<td>L</td>
</tr>
<tr>
<td></td>
<td>Compton Backscatter</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td>Saturated Low Frequency Eddy Current</td>
<td>H</td>
</tr>
<tr>
<td>Blisters and embedded horizontal cracks, delamination</td>
<td>UT Pulse-echo 0 deg. compression wave</td>
<td>H</td>
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<td></td>
<td>UT mapping (C-scan)</td>
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<td></td>
<td>Phased Array</td>
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<tr>
<td></td>
<td>Pulsed Thermography</td>
<td>M</td>
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<tr>
<td></td>
<td>Shearography</td>
<td>L</td>
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<tr>
<td></td>
<td>UT TOFD</td>
<td>H</td>
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<tr>
<td></td>
<td>Compton Backscatter</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td>Acoustic Emission</td>
<td>L</td>
</tr>
<tr>
<td>Surface breaking cracks</td>
<td>Eddy Current ACFM (inspection surface only)</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td>Phased Array</td>
<td>H</td>
</tr>
<tr>
<td></td>
<td>Liquid Penetrant (inspection surface only)</td>
<td>H</td>
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<tr>
<td></td>
<td>Magnetic Particle Inspection (inspection surface only)</td>
<td>H</td>
</tr>
<tr>
<td></td>
<td>UT Pulse-echo Shear wave (backwall &amp; frontwall)</td>
<td>H</td>
</tr>
<tr>
<td></td>
<td>UT TOFD (backwall &amp; frontwall)</td>
<td>H</td>
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<td></td>
<td>Guided Wave</td>
<td>M</td>
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<tr>
<td></td>
<td>Acoustic Emission (backwall &amp; frontwall)</td>
<td>M</td>
</tr>
<tr>
<td>Embedded cracks</td>
<td>UT Pulse-echo Shear wave</td>
<td>H</td>
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<tr>
<td></td>
<td>UT TOFD</td>
<td>H</td>
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<tr>
<td></td>
<td>Phased Array</td>
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<td></td>
<td>Film Radiography</td>
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<td></td>
<td>Computed Radiography</td>
<td>M</td>
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<tr>
<td></td>
<td>Acoustic Emission</td>
<td>M</td>
</tr>
<tr>
<td>Flaw type</td>
<td>Inspection method</td>
<td>Inspection efficiency</td>
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<td>---------------------------</td>
<td>--------------------------------------------------------</td>
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<tr>
<td></td>
<td></td>
<td>Detection</td>
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<tr>
<td></td>
<td></td>
<td>Through wall Sizing</td>
</tr>
<tr>
<td>Embedded volumetric voids</td>
<td>UT Pulse-echo 0 deg. compression wave</td>
<td>M</td>
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<td></td>
<td>UT Pulse-echo Shear wave</td>
<td>M</td>
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<td></td>
<td>UT TOFD</td>
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<td>Phased Array</td>
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<td>Film Radiography</td>
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<td></td>
<td>Shearography</td>
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<td></td>
<td>Pulsed Thermography</td>
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<td></td>
<td>Computed Radiography</td>
<td>H</td>
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<tr>
<td>Anomalies</td>
<td>Thermography</td>
<td>M</td>
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<td></td>
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<tr>
<td>Weld root erosion</td>
<td>UT TOFD</td>
<td>H</td>
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<tr>
<td></td>
<td>UT Pulse-echo Shear wave</td>
<td>M</td>
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<tr>
<td></td>
<td>UT Pulse-echo 0 deg. compression wave (if weld cap removed)</td>
<td>M</td>
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<td></td>
<td>Phased Array</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td>UT mapping (C-Scan) (if weld cap removed)</td>
<td>H</td>
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<tr>
<td></td>
<td>Pulsed Thermography</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td>Film Radiography (double wall method)</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td>Computed Radiography (tangential on pipes)</td>
<td>H</td>
</tr>
</tbody>
</table>

- = Not applicable
### Table A-2 Capabilities of Non-intrusive Inspection Methods

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</tr>
</thead>
<tbody>
<tr>
<td>1. UT Pulse-echo Shear wave</td>
<td>6-300</td>
<td>Reduced capability for austenitic and duplex welds</td>
<td>Up to 250°C using special probes</td>
<td>uniform coating up to 1.5 mm</td>
<td>1 mm-5 mm depending on geometry</td>
<td>±3 mm mean error for weld inspection</td>
<td>Weld 20m/day</td>
<td>high POD values published</td>
<td>ID</td>
<td>Surface and embedded crack, volume</td>
<td>Capability for weld inspection depends on geometry and UT procedure</td>
<td>small probe</td>
<td>Well-bonded coating can be allowed. Vessel features such as supports, saddles and reinforcement plates cause non-inspectable areas for spot inspection.</td>
</tr>
<tr>
<td>2. UT Pulse-echo 0° compression wave</td>
<td>2-300</td>
<td>Reduced capability for austenitic and duplex welds</td>
<td>Up to 250°C using special probes</td>
<td>uniform coating up to 1.5 mm</td>
<td>0.5mm WT typical, depending on thickness</td>
<td>digital thickness gauge ±0.1mm ideal, ±0.5mm typical</td>
<td>spot 1000/day</td>
<td>high POD values published</td>
<td>ID/OD</td>
<td>local WTL, volume, blistering,</td>
<td>Surface</td>
<td>small probe</td>
<td>Well-bonded coating can be allowed. Vessel features such as supports, saddles and reinforcement plates cause non-inspectable areas for spot inspection.</td>
</tr>
<tr>
<td>3. UT corrosion mapping C-Scan 0° compression wave</td>
<td>2-300</td>
<td>As pulse-echo UT</td>
<td>Up to 125°C (longer contact)</td>
<td>As pulse-echo UT</td>
<td>0.5mm WT typical, depending on thickness</td>
<td>±0.1 mm ideal ± 0.5mmtypical</td>
<td>2-3 m², 8-12 m² paint-brush, Up to 16 m² mechanized</td>
<td>High POD values published</td>
<td>ID</td>
<td>local WTL, blistering</td>
<td>Surface</td>
<td>probe and encoder or mechanized vehicle on magnetic enforced wheels</td>
<td>Patches of 250 × 500 mm per scan. Coloured WT map. Post inspection data manipulation when Pscan is used.</td>
</tr>
<tr>
<td>4. UT TOFD</td>
<td>8-300</td>
<td>Restricted to fine grain material</td>
<td>As pulse-echo UT</td>
<td>As pulse-echo UT</td>
<td>3mm depending on geometry</td>
<td>±0.5 mm ideal, ±2 mm typical</td>
<td>Weld 40m/day</td>
<td>high POD values published</td>
<td>ID, embedded</td>
<td>Embedded and surface crack, volume</td>
<td>Corner welds, complex geometries</td>
<td>scooter or guiding belt</td>
<td>Fast weld scanning. Post inspection data interpretation. Dead zone up to 2 – 4 mm below the surface</td>
</tr>
<tr>
<td>5. UT CHIME</td>
<td>Up to 40</td>
<td>As pulse-echo UT</td>
<td>Current applications up to c. 60°C</td>
<td>As pulse-echo UT</td>
<td>Min. c. 10% of WT. Lateral dimension &gt; 15 mm</td>
<td>10 mm on position</td>
<td>Scan speed c. 1m/min.</td>
<td>Medium POD values published</td>
<td>no ID/OD discrimination</td>
<td>general and local WTL, cracking</td>
<td>Reinforcement plates, saddles, supports. Also shell screening</td>
<td>manipulator and probe</td>
<td>No quantitative signal, degree of damage can be assessed.</td>
</tr>
<tr>
<td>6. UT Long Range (Lamb Wave)</td>
<td>All pipes from 2 to 48 inc diameter</td>
<td>Normally carbon steel pipes only</td>
<td>-25 to 125°C. Special equipment up to 160°C</td>
<td>Similar to pulse-echo UT. Bare metal best.</td>
<td>Min. 5 – 9% of pipe wall circumferential area</td>
<td>Typically 1 km/day</td>
<td>Medium POD values published</td>
<td>no ID/OD discrimination</td>
<td>local WTL, cracking</td>
<td>Pipes – typically straight (few bends)</td>
<td>Probes form ring around pipe. Access to 0.5 m of bare pipe needed</td>
<td>Works best on straight pipes. Probe ring needs to be at least 1 m from nearest girth weld. Some pipe coatings limit range of method (e.g. Bitumasic)</td>
<td></td>
</tr>
<tr>
<td>Inspection Method</td>
<td>Wall thickness [mm]</td>
<td>Material</td>
<td>Temperature Range</td>
<td>Surface Finish</td>
<td>Sensitivity / min. detectable flaw</td>
<td>Accuracy / Repeatability</td>
<td>Productivity</td>
<td>Method Maturity</td>
<td>Flaw location</td>
<td>Flaw type</td>
<td>Vessel feature application</td>
<td>Access restriction</td>
<td>Limitations / Comments Testing req.'s</td>
</tr>
<tr>
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</tr>
<tr>
<td>7. UT EMAT</td>
<td>10-150</td>
<td>As pulse-echo UT</td>
<td>-200°C to 460°C</td>
<td>Rough surface acceptable in principle but reduces sensitivity even further</td>
<td>As pulse-echo UT under ideal circumstances, typically much poorer</td>
<td>As pulse-echo UT</td>
<td>low</td>
<td>ID</td>
<td>As pulse-echo UT</td>
<td>As pulse-echo UT</td>
<td>small probe</td>
<td>Sensitivity much lower than conventional UT probes. Main application is for wall thickness measurements on magnetic coated components. Non-contact UT possible</td>
<td></td>
</tr>
<tr>
<td>8. Eddy Current ACFM</td>
<td>N/A</td>
<td>All</td>
<td>up to 150°C</td>
<td>coating allowed with restrictions</td>
<td>Crack depth &gt; 1 mm and length &gt;10mm ideal, depth &gt;3mm and length &gt;20mm typical</td>
<td>±3mm</td>
<td>Medium</td>
<td>High</td>
<td>OD only</td>
<td>crack undercoating</td>
<td>welds, surface limited</td>
<td>small probe</td>
<td>Multi element surface scan coils, possible crack depth measurement. Rust and ferromagnetic debris may influence the inspection. Flaw free sample needed for calibration.</td>
</tr>
<tr>
<td>9. Pulsed Eddy Current</td>
<td>6-60 (through max. 150 mm insulation)</td>
<td>Low alloy C steel, restricted by ferromagnetic sheeting</td>
<td>-100°C to 500°C contact temperature max. 70°C</td>
<td>non contact, through insulation</td>
<td>5% WT (relative measurement)</td>
<td>1,000 points/day</td>
<td>medium POD values published</td>
<td>medium POD values published</td>
<td>Insulate, no ID/OD discrimination</td>
<td>general WTL, volume</td>
<td>surface spot</td>
<td>probe 100 - 250 mm</td>
<td>Detect general corrosion or erosion if area exceeds (500 mm²), no pitting, influence of nearby metal mass</td>
</tr>
<tr>
<td>10. Saturated Low Frequency Eddy Current</td>
<td>Up to 30 - 35 all, wall thickness for ferromagnetic, reduced capability for other but same as EC.</td>
<td>up to 60°C</td>
<td>non contact, max. 8 mm coating</td>
<td>15% WT</td>
<td>10 – 50 m² / day</td>
<td>Medium</td>
<td>ID/OD discrimination possible</td>
<td>local WTL, volume</td>
<td>Surface</td>
<td>heavy device due to magnets</td>
<td>Fast large area scanning. Down to 1.4 mm³ volume wall loss can be detected under favourable conditions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11. Liquid Penetrant (incl. dye and fluorescent)</td>
<td>N/A</td>
<td>All, non-porous</td>
<td>10°C to 50°C</td>
<td>Free of scale, slag, rust, oil, grease or paint.</td>
<td>Anything visible</td>
<td>-</td>
<td>20 m per day</td>
<td>high POD values published</td>
<td>OD only</td>
<td>surface crack</td>
<td>all geometry’s</td>
<td>N/A.</td>
<td>Very clean surface needed. Less reliable than MPI for ferromagnetic material</td>
</tr>
<tr>
<td>12. Magnetic Particle Inspection (incl. fluorescent)</td>
<td>N/A</td>
<td>Ferromagnetic</td>
<td>up to 100°C</td>
<td>Free of scale, slag, rust, oil, grease or paint. Smooth surface increases reliability</td>
<td>Anything visible</td>
<td>-</td>
<td>40 m per day</td>
<td>high POD values published</td>
<td>OD only</td>
<td>surface crack</td>
<td>depending on yoke</td>
<td>yoke size 300 mm</td>
<td>Contrast paint can be used. Dry test ‘ink’ for high temperatures</td>
</tr>
<tr>
<td>13. Magnetic Flux Leakage</td>
<td>4-10</td>
<td>Ferromagnetic</td>
<td>up to 60°C</td>
<td>max. 3 mm coating, clean surface</td>
<td>min. 30% WT or 20mm³</td>
<td>-</td>
<td>10 –50 m² / day</td>
<td>High POD values published</td>
<td>no ID/OD discrimination</td>
<td>local WTL</td>
<td>Surface</td>
<td>medium size device 300 x 300 mm</td>
<td>Fast large area scan. Wall and pipescan, not floorscan</td>
</tr>
</tbody>
</table>

Table A-2 Capabilities of Non-intrusive Inspection Methods (Continued)
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</tr>
</thead>
<tbody>
<tr>
<td>14. Pulsed Thermography</td>
<td>Surface N/A</td>
<td>-20 to 1000°C</td>
<td>Depends on the surface emissivity</td>
<td>Temperature variations of 0.2°C at 1 m; 10°C at 100 m.</td>
<td>-</td>
<td>Depends on application</td>
<td>high</td>
<td>OD, screening for internal flaws</td>
<td>anomalies</td>
<td>Surface N/A</td>
<td>Screening for anomalies</td>
<td>-20 to 1000°C</td>
<td>-depends on the surface emissivity of the specimen and the distance. Filters above 500°C. Line-of-sight required.</td>
</tr>
<tr>
<td>15. Film Radiography</td>
<td>Ir 192 Up to c.100 penetrated thickness. Higher with Co60.</td>
<td>max. 40°C</td>
<td>N/A</td>
<td>2%WT</td>
<td>slow depends on access and radiation safety regulations. Can be speeded up by use of SCAR or SafeRAD containers</td>
<td>high</td>
<td>ID/OD embedded</td>
<td>local and general WTL</td>
<td>embedded volumetric flaws</td>
<td>critical WT locations, welds, nozzles,</td>
<td>2 sided access</td>
<td>Double wall technique limited to vessels diameter below 1.5 m. Tangential technique, on stream possible. Radiation safety restrictions.</td>
<td></td>
</tr>
<tr>
<td>16. Computed Radiography</td>
<td>Similar to film radiography</td>
<td>All</td>
<td>N/A</td>
<td>2% WT</td>
<td>Generally faster than film radiography subject to sensitivity. Depends on access and radiation safety regulations</td>
<td>medium</td>
<td>ID/OD</td>
<td>local and general WTL</td>
<td>As Film Radiography</td>
<td>2 sided access, manipulator movement</td>
<td>-20 to 1000°C</td>
<td>-30°C</td>
<td>On stream. Radiation safety restrictions.</td>
</tr>
<tr>
<td>17. Acoustic Emission</td>
<td>All</td>
<td>Normal maximum 60°C</td>
<td>As 1 and 2 local to probes</td>
<td>Only detects growing flaws</td>
<td>Information on position</td>
<td>whole vessel</td>
<td>medium</td>
<td>ID/OD embedded</td>
<td>propagating cracks, crack/corrosion initiation</td>
<td>Whole vessel</td>
<td>small probes</td>
<td>extremely sensitive to environmental influences</td>
<td></td>
</tr>
</tbody>
</table>

Remarks:
Material: Carbon steel, stainless steel (including Inconel), duplex
Productivity: speed under normal conditions
Method maturity: experience with method, (low/medium/high) and POD values known
Flaw location: OD is near (probe) side, discrimination of ID/OD flaws possible, embedded flaws can be found
Flaw type: damage description, main character of method. WTL is wall thickness loss. Local WTL is pitting. Cracks can be surface breaking or embedded.
Vessel feature application: type of features suitable for inspection. Welds: butt, corner or complex geometry. Surface with full area access (inspected area is equal to probe access area). Volume means inspected material volume and probe contact location are not necessarily the same
Access (restrictions): seen from the NDT method, the required access area. In most cases determined by the probe size (detached units).

POD References:
APPENDIX B
STATISTICAL APPROACHES TO NII

B.1 Use of Statistical Methods in NII

B.1.1 Background

A range of statistical methods can be used to help quantify various aspects of the NII inspection procedure. This appendix presents some of the principal methods that can be used to assist in inspection scheduling, as well as the evaluation of inspection data.

The first section discusses a statistically based approach to setting the inspection interval in order to ensure safe operation. Two examples of statistical methods which can be useful tools for evaluation of inspection data from non-intrusive inspection are also provided.

The first method is extreme value statistical analysis, which can be useful for predicting what the maximum corrosion pit depth in a vessel zone is, based on a sample inspection for pitting within that zone. It can also be used to help determine what the sample size should be in order to achieve a particular level of confidence in the conclusions.

The second example covers the use of statistical methods to determine what the probability of detecting at least one flaw (and therefore revealing that a particular degradation mechanism is active) as a function of sample size and how widespread the degradation is.

B.2 Statistical Basis for Inspection Scheduling

Traditionally, inspection intervals are often specified on the basis of legislative requirements. More recently however, risk considerations have been taken into account. If non-intrusive inspection (NII) is to be used in conjunction with or as an alternative to IVI then a sensible basis for the determination of the NII requirements would be to ensure that the risk levels are not increased. For any given vessel this effectively means that there should not be an increase in the probability of failure (POF) when NII is used.

The approach suggested here aims to compare the nature of evolution of the probability of failure under different assumed inspection regimes. This comparison is then used in developing a basis for the determination of an acceptable NII strategy.

B.2.1 Probability of Failure

The probability of failure is determined as the probability that a defect will exist with a size larger than the critical size. Given a known probability distribution for the sizes of the flaw population and a known critical defect size, the probability of failure can be calculated as the area under the distribution curve for defects larger than the critical size.

In many cases the critical defect size will not vary with time, however, the probability distribution will typically be time dependent as a result of flaw growth by a variety of potential mechanisms. The nature of growth with time therefore has a direct influence on the probability of failure. With growth, there is a greater probability of defects exceeding the critical size hence the probability of failure will tend to increase with time.

Inspection, aimed at identifying and sizing flaws, along with appropriate action (e.g. repair, rejection) taken when defects exceed a certain size will have the effect of reducing the probability of failure. This is a consequence of the probability distribution being modified for defect sizes larger than a defined acceptable limit.

The nature of the reduction in probability of failure is directly related to the probability of detection (POD) of the inspection performed. An inspection with a 100% POD of defects larger than the acceptable limit would reduce the probability failure to zero. Hence the probability distribution, as defined by \( p(x) \), before and after the inspection might appear as shown in Figure B-1.

Note that in practice there would be some modification of the curve for flaws smaller than the acceptable size due to imprecision in the inspection method giving rise to false calls. This, however, will not be considered here and it will be assumed for the present purposes that the inspection method has a 0% false call rate.

\[
\int_{x_{\text{crit}}}^{\infty} p(x)dx
\]

Figure B-1
Effect of Inspection with POD = 1 on Probability Distribution

Few inspections will provide a 100% POD hence the case shown in Figure B-1 is not typical. More commonly the POD will be less than one and may be a function of flaw size. Hence inspection will have the effect of reducing in some way the probability of defects larger than the acceptable size rather than eliminating it. A more typical case is thus as illustrated in Figure B-2.

\[
\int_{x_{\text{accept}}}^{\infty} p(x)dx
\]

Figure B-2
Effect of Inspection with POD < 1 on Probability Distribution

For a probability distribution before the inspection given by \( p_s(x) \) and a probability of detection defined by \( POD(x) \), the probability distribution after inspection is given by

\[
p_s(x) = p_s(x) \quad \text{for } x \leq x_{\text{accept}}
\]

\[
p_s(x) = (1 - POD(x)) \cdot p_s(x) \quad \text{for } x > x_{\text{accept}}
\]

(1)

The probability of failure before the inspection is given by

\[
POF_s = \int_{\infty}^{x_{\text{crit}}} p_s(x)dx
\]

(2)
and after inspection by

$$POF_x = \int_{x_i}^x (1 - POD(x)) p(x) dx$$

Clearly, the greater the POD of the inspection, the lower the probability of failure after the inspection. This lower probability is retained in part up to the time of the next inspection through the modifying effect on the probability distribution. The way the latter evolves between inspections however depends very much on the nature of flaw growth in addition to its form directly after the inspection. Growth means that the flaw distribution is time dependent and hence so is the probability of failure, which will tend to increase during time intervals between inspections. The shorter these intervals (i.e. the greater the frequency of inspection) the lower the probability of failure will be. In addition to being a function of flaw growth in between inspections, the form of the flaw distribution after an inspection is also dependent on the probability of detection and the margin between acceptable and critical defect sizes. Hence it can be concluded that the probability of failure is primarily a function of time (which defines the growth processes), the inspection interval, the probability of detection of the inspection and the margins between acceptable and critical defect sizes.

Since the growth processes are very often dominated by the equipment design and operating conditions, control over the probability of failure is typically only possible through variation of the inspection interval, the probability of detection and the margins between acceptable and critical defect sizes. The definition of acceptable defect size is often out of the operator’s hands hence safe management relies largely on a suitable specification of inspection interval and method (as the latter defines the POD).

In order to gain some insight into how the interval and POD may affect probability of failure it is useful to consider some representative examples.

The case to be considered assumes a growth process in which the growth rate is, on average, constant but allows for some variation in rate as defined by a normal distribution. This would be typical of corrosion type processes.

In this scenario, the growth of any flaw over a specified time interval is given by a normal distribution, this being defined by

$$G(x, \mu, \sigma) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

where

- $\mu$ is the average growth
- $\sigma$ is the standard deviation of the growth

For flaws whose initial sizes are in the range $x_i$ to $x_i + \delta x$, the size distribution at the end of the specified interval is given by

$$F(x, x_i) = f_i G(x, x_i + \mu, \sigma)$$

where $f_i$ is the proportion of the total flaw population made up of flaws covering the initial size range. For an initial flaw population distribution given by the continuous function $p(x)$, the proportion of flaws covering the range $x_i$ to $x_i + \delta x$ can be approximated by

$$f_i = p(x_i) \delta x$$

In order to determine the flaw size distribution $S(x)$ at the end of the period, the growth of the entire population of flaws must be considered, this being achieved by summation of the individual distributions as follows

$$S(x) = \sum_{i} F(x, x_i) = \sum_{i} p(x_i) G(x, x_i + \mu, \sigma) \delta x$$

In the limit as $\delta x \to 0$, the above becomes

$$S(x) = \int_0^x p(y) G(x, y + \mu, \sigma) dy$$

With no inspection at the end of the period, the starting distribution for the next period is given directly by $S(x)$ and this can be used in the integration of equation (2) to obtain the distribution at the end of the period.

When an inspection is carried out, the distribution before the inspection is $S(x)$ and after the inspection it is modified by the reduction in the probability of defects having size larger than acceptable, as follows

$$S_{i+1}(x) = S(x)$$

for $x \leq x_{\text{accept}}$

$$S_{i+1}(x) = (1 - POD(x)) S(x)$$

for $x > x_{\text{accept}}$

The above values are then used to define the flaw distribution at the start of the next time period. By recursively updating the flaw distribution in this way, the probability of failure can be tracked throughout the life of a vessel and the effects of different inspection strategies (e.g. variations in the interval between inspections and the probability of detection) can be studied.

Figure B-3 shows some typical results which illustrate the effect of variations in the inspection interval and the probability of detection.

The uppermost solid curve shows the situation when there is no inspection performed and, as expected, the probability of failure increases continuously with time. Moving downwards, the next solid curve shows the evolution of POF for the case of inspections with POD=0.5 at every tenth time period. The reduction in POF following each inspection is clearly visible. This reduction is observed to nearly match the rise in POF over the time since the preceding inspection hence, on average, the POF is retained nearly constant under this inspection strategy. The figure shows that a similar average POF can be maintained by adopting an alternative strategy in which the inspection interval is reduced to 5 time periods and the POD also reduced (to 0.3).

The curves for POD=0.5 with an interval of 5 time periods and POD=0.8 with an interval of 10 time periods show, as expected, that the effect increasing POD is to lower the POF. Again it is clear that a given nominal POF at any time can be achieved by variation of either POD or inspection interval. There will however be differences within the time between inspections and a very long inspection interval may lead to an unacceptably high POF even if preceded by a high POD inspection.
B.2.2 Practical considerations

In practice, due to a large number of uncertainties, it will often be very difficult to quantify the probability of failure, as outlined above, with sufficient confidence. Hence such an approach may not always be adequate in providing reliable guidance for the definition of inspection interval and type. There is however a need that these be defined in a systematic manner and this is addressed in a variety of codes of practice (see for examples Refs. [10, 11, 22]) and many organisations have developed their own guidance documents.

Given that internal visual inspection has historically been the primary method, most industry accepted approaches a directed at this type of inspection. However, the principles remain applicable to the specification of NII. A common approach is to base the inspection interval for IVI on the Inspection Grade assigned to the vessel. Guidance on the determination of Inspection Grade may vary according to the code used however it effectively depends on:

— the history of previous inspection intervals
— the confidence in knowledge of the degradation rates
— the maximum degradation rate considered possible.

Grade 0 is the most severe and demands the shortest inspection interval and the interval increases with each Grade until it is a maximum for Grade 3. In order for a vessel to advance a grade it should typically have at least one inspection at the preceding grade. This is where the history of previous inspection intervals plays a role in determining grading.

Reduced confidence in knowledge of the degradation rates has the effect of reducing inspection grade (and hence also shortening the inspection interval). This effectively takes a conservative approach to reducing probability of failure when faced with uncertainty.

Likewise the inspection grade reduces with increasing degradation rate. This is aimed at ensuring the probability of failure remains more or less constant, even for different deterioration mechanisms.

Specification of inspection interval according to grade only does not take risk into account in a systematic way. Risk based inspection (RBI) is becoming increasingly accepted as offering a technically sound yet cost effective means of managing plant safety. Risk is determined as the product of the probability of failure and the consequences of failure and RBI aims to ensure that risk is consistently maintained at an acceptably low level. This can be achieved by a variety of means but the primary variables are inspection interval and inspection type. When internal visual inspection is relied upon, control of risk comes down to specification of an appropriate inspection interval, i.e. high risk items demand a short interval while longer inspection intervals are acceptable for low risk items.

Different guidelines have been developed for the specification of inspection interval according to risk. In many cases (e.g. Refs. [23, 24]) the interval is not specified according to risk alone but also takes into account the inspection grading. The interval is then defined according to the combination of risk ranking and inspection grade. Typically, rules might be as shown in Table B-1. (Note that these rules are not generic and may vary for different applications, risk ranking definitions etc.)

<table>
<thead>
<tr>
<th>Criticality</th>
<th>Inspection Grade</th>
<th>Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12</td>
<td>36</td>
</tr>
<tr>
<td>2</td>
<td>24</td>
<td>36</td>
</tr>
<tr>
<td>3</td>
<td>24</td>
<td>48</td>
</tr>
<tr>
<td>4</td>
<td>36</td>
<td>48</td>
</tr>
<tr>
<td>5</td>
<td>36</td>
<td>48</td>
</tr>
</tbody>
</table>

In the table Criticality defines the risk ranking with Criticality = 1 being the highest and Criticality = 5 being the
lowest risk rankings respectively. In the above rules, it would be specified that Criticality 1 items cannot be assigned a grade higher than 1 and Criticality 2 items cannot be assigned a grade higher than 2.

Items having high risk and low inspection grade (top left) have short inspection intervals while low risk, high grade (bottom right) items have longer intervals. Taking into consideration the combination of risk and grade in this way may be regarded as doubly accounting for risk. This is true only to the extent that the grade is a measure of the probability of failure. However, grade does not consider the consequence of failure in any way. In addition, risk may not, in general, consider the history of previous inspection intervals. Hence taking a combination of risk and grade into account does allow for a more complete basis for the specification of inspection interval and results in greater differentiation in the requirements for different vessels. In a sense using the combination refines the scale of interval that can be specified compared to the case when only one or the other is considered.

It is important to recognise that the type of inspection has to be considered in determining risk. An inspection having high effectiveness will lead to a reduction in risk and vice versa.

In most cases inspection intervals will already have been specified assuming that IVI will be carried out. Once it has been determined that NII is possible and applicable at a given inspection, the interval following the NII can then be adjusted taking into consideration the inspection effectiveness.

The flow charts set up for use as guidance in selecting an appropriate NII method assign efficiency rankings to each method according to the application. The ranking is defined such that, for areas covered by the inspection:

- **High**: the NII method has a markedly higher POD than IVI
- **Medium**: the NII method has broadly similar POD to IVI
- **Low**: the NII method has a markedly lower POD than IVI.

In keeping with the goal of maintaining a constant long term probability of failure, the decision process uses the effectiveness of the previous inspection as an input to determining the minimum efficiency required of the current inspection. Credit can be taken for a high effectiveness inspection by allowing a low effectiveness for the following inspection (assuming of course that other factors considered allow it). Alternatively, an inspection having a low effectiveness may need to be followed by one having a high effectiveness in order to maintain the desired probability of failure.

Given that at this stage of the project the timing of the inspection is taken as given, all that can be specified is the method efficiency requirement. It is clear, however, that control of the probability of failure could be more effective by allowing for changes in interval according to the method used. This would make for greater flexibility in developing and adapting an NII strategy to meet plant specific requirements. For example, it could allow the user to specify more frequent lower efficiency (and perhaps lower cost) NII while still maintaining a comparable probability of failure to what would be achieved with IVI at longer intervals.

**B.3 Bayes’ Theorem**

Bayes’ theorem provides a logical way of updating incomplete knowledge (e.g. 75% confident no degradation present) based on a test or observation which itself may not be 100% reliable (e.g. inspection method detects degradation 90% of the time).

Bayes’ theorem states that given that event B has occurred, the probability that it was due to cause A is equal to the probability that A should produce that event times the probability that A should occur in the first place, all divided by a scaling factor which is the sum of such terms over all causes. For example, if it is assumed that before inspection of a particular plant item, there is a 75% confidence that there was no degradation present. If the item is now inspected, using a method with a 90% probability of detecting degradation, with no false calls, and no degradation is reported, Bayes’ theorem can be used to determine the revised probability that there is in fact no degradation.

In this case the event “B” is that no degradation is reported, and the “cause” A1 is no degradation present. However another possible cause is that degradation is present (but missed). The notation p(A / B) means “the probability of A, given B” according to Bayes’ theorem:

\[
\text{prob} (\text{no degradation present} | \text{none reported}) = \frac{(\text{prob. none reported} \times \text{none present})}{(\text{prob. none reported} \times \text{none present}) + (\text{prob. none reported} \times \text{present} \times \text{prob. present})}
\]

\[
= \frac{1 \times 0.75}{(1 \times 0.75) + (0.1 \times 0.25)} = 0.968
\]

i.e. the confidence that no degradation is present has therefore increased from 75% to around 97%.

Bayes’ theorem can also be used to support decisions based on expert judgement even where precise quantitative data on inspection effectiveness or likelihood of degradation does not exist. For example expert judgement could be used to assign a category to inspection effectiveness such as “very high”, “medium high”, “medium” etc. where each category is taken to represent a band such as “better than 90%”, “between 75% and 90%” etc. A similar approach could be adopted to describe initial likelihood of degradation (or degradation rate). The average within each band (e.g. 95% for very high) could then be used to apply Bayes’ theorem. Depending on the band within which the “answer” lay, the revised likelihood of degradation (or degradation rate) could then be interpreted in the original linguistic terms (very high, high etc.)

Note that care should be taken when using probability of detection (POD) data in Bayes’ theorem in cases where a number of discrete flaws (e.g. cracks) may be present. A method with a POD of 90% will have a 90% probability of detecting each individual flaw, but a much lower probability of detecting all of the flaws.

**B.4 Extreme Value Statistical Analysis**

There is a common requirement to monitor the condition of plant for reasons of safety or in order to plan the repair or replacement of plant components during their working life. For example a chemical plant may have several vessels that require examination to assess the severity of internal corrosion present. This could be done by carrying out a detailed inspection of the inside of a vessel, and mapping the areas of corrosion. This would inevitably mean that the plant would need to be shut down in order to carry out such an inspection. An alternative would be to carry out an ultrasonic thickness survey of the entire vessel from the outside surface. The advantage of using such a method would be that the plant may not need to be opened or even shut down in order to carry out the inspection. However, the vessel may be large, requiring a long time to carry out the ultrasonic survey. Another way to assess the corrosion present would be to carry out a survey on a representative area of the vessel and use statistical techniques to predict the condition of the entire vessel from the results of the representative area. The advantages of using this technique would be a saving in time and therefore cost of inspection.
The corrosion process can be complicated, with several corrosion mechanisms taking place simultaneously. To fully understand the mechanisms taking place can require extensive testing and analysis in the laboratory. However, corrosion can be classified into two broad categories: uniform and non-uniform (or localised) corrosion. Illustrations of these two categories are shown in Figure B-4.

![Corrosion Categories](image)

When a statistical sample is taken a distribution of results is produced from which certain things can be measured, such as the mean and the variance (or Standard Deviation) of the distribution. If we applied this method of sampling to our vessel corrosion problem we could gain valuable information about the severity of corrosion within the vessel and we would also have quantitative information with which to compare previous and future inspections. This type of analysis is useful where the corrosion within the vessel is known to be uniform. In which case we would be more interested in the average or mean depth of corrosion.

If we carried out an ultrasonic thickness survey on a vessel with uniform corrosion we would expect to find a Gaussian or Normal type of distribution from our measurement data. The Gaussian or Normal type of distribution is illustrated in Figure B-5. Our measurements would show a spread of results symmetrically about the mean value.

We could use statistical techniques to measure the mean value and calculate the standard deviation or variance of the distribution. This would provide us with a measure of the spread of values in our distribution.

![Gaussian or Normal Distribution](image)

In the case of non-uniform corrosion we would be more likely to be interested in the deepest extent of the corrosion present, as a single through wall pit will cause the component to leak. If we used the statistical tools we used on the uniform corrosion we may underestimate the seriousness of the deepest corrosion present on the component. A different technique needs to be used in this case; one where we concentrate our measurement and statistical techniques on the most extreme depths of corrosion.

Some corrosion processes occur which are non-uniform where local areas can be subject to extreme degradation (e.g. pitting). With a non-uniform corrosion process we would be much more interested in the most extreme values from our ultrasonic survey, as relying on average or mean values may lead us to be too optimistic in our assessment of plant condition. The branch of statistics which deals with the analysis of these extreme values is “Extreme Value Statistical Analysis” (Ref. 25).

This statistical analysis will be described by way of an example, where we are required to assess the deepest extent of corrosion on the inside surface of a large pressure vessel using ultrasonic thickness measurements. We know that the corrosion occurring in the inside of the vessel is consistent over the entire inner surface but the corrosion is non-uniform in that we know that severe corrosion pitting is occurring. Therefore we can use our extreme value techniques to predict the deepest corrosion likely to be present on the vessel.

### B.4.1 Obtaining the Data

When carrying out a survey for Extreme Value Statistical Analysis we place more statistical relevance to the extreme maximum (or extreme minimum) values measured. In terms of a normal statistical distribution we are in effect analysing the tail of the normal distribution and using statistical techniques to derive probability functions which we can use to gain quantitative information about the most extreme corrosion occurring in the component.

Let us examine the case where we need to carry out a survey of the non-uniform corrosion pitting (or other severe corrosion processes) within a large pressure vessel. We know that the corrosion is non-uniform as there is severe corrosion present generally over the entire inner surface of the vessel. One way of obtaining a statistical sample for extreme value statistical analysis would be as follows:

- choose a representative area of the vessel, say a convenient area of 1 m × 2.1 m. (Note: the area should be “representative" of the condition of the whole vessel or of the part of the vessel being considered)
- split the examination area into sub-areas, say 100 mm × 100 mm squares
- carry out a detailed ultrasonic examination of each sub-area and record only the most extreme value for pitting depth measured in each sub-area.

We now have a sample which we can analyse using extreme value techniques. There are 210 values which we can display in the form of a histogram, see Figure B-6. The x axis measures increasing depth of pitting and the y axis records quantity i.e. number of readings of this depth of corrosion.
B.4.2 Processing the Data

The histogram showing our results is called a “frequency distribution”. Because it has been produced from a process which concentrates on extreme values however, it does not display the normal or Gaussian symmetrical pattern. The extreme values recorded, tend to trail off at the right hand side of the distribution. In order to process our data we need to find a function which will model our distribution. A distribution function called a “double exponential” or “Gumbel” distribution is commonly used to model such a “maximum” distribution.

The Gumbel distribution function takes the form:

\[ F(x) = \exp\left[-\exp\left(-\frac{x-\lambda}{\alpha}\right)\right]; \quad -\infty < x < \infty \quad (10) \]

\[ f(x) = \frac{1}{\alpha} \exp\left(-\frac{x-\lambda}{\alpha}\right) \exp\left(-\exp\left(-\frac{x-\lambda}{\alpha}\right)\right); \quad -\infty < x < \infty \]

---

Table B-2  Example data for Extreme Value Statistical Analysis

<table>
<thead>
<tr>
<th>Local Maxima of Pitting/Corrosion (mm)</th>
<th>Frequency A (number)</th>
<th>Probability Density Function ( f = A/(N + 1) )*</th>
<th>Cumulative Distribution Function ( F = \sum f )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>19</td>
<td>0.090</td>
<td>0.090</td>
</tr>
<tr>
<td>0.4</td>
<td>40</td>
<td>0.190</td>
<td>0.280</td>
</tr>
<tr>
<td>0.6</td>
<td>43</td>
<td>0.203</td>
<td>0.483</td>
</tr>
<tr>
<td>0.8</td>
<td>43</td>
<td>0.203</td>
<td>0.686</td>
</tr>
<tr>
<td>1.0</td>
<td>31</td>
<td>0.138</td>
<td>0.834</td>
</tr>
<tr>
<td>1.2</td>
<td>15</td>
<td>0.071</td>
<td>0.905</td>
</tr>
<tr>
<td>1.4</td>
<td>12</td>
<td>0.057</td>
<td>0.962</td>
</tr>
<tr>
<td>1.6</td>
<td>4</td>
<td>0.019</td>
<td>0.981</td>
</tr>
<tr>
<td>1.8</td>
<td>2</td>
<td>0.010</td>
<td>0.991</td>
</tr>
<tr>
<td>2.0</td>
<td>1</td>
<td>0.004</td>
<td>0.995</td>
</tr>
<tr>
<td>Total (N)</td>
<td>210</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Using the “Average Rank Method”. See referenced text.

---

The table includes two columns containing useful information on our distribution which we will present graphically: The “Probability Density Function” (see Figure B-7) and the “Cumulative Distribution Function” (see Figure B-8). These functions are derived from our recorded data.
In order to check that our Gumbel model is a valid description of the distribution it is necessary for us to plot the function:

\[ Y = -\ln[-\ln(F(x))] \]

This has been done for our results presented in Table B-2 and is shown in Figure B-9.
Figure B-9
Verification of Gumbel Function

Figure B-9 clearly shows a good linear relationship for the plotted function $Y$. This linearity indicates that the assumption of a Gumbel function being a good statistical model is valid for our data. The parameters $\lambda$ and $\alpha$ from equation (10) can be determined from the graph; $\lambda$ is the slope of the graph and $\alpha$ corresponds to the intercept at $y = 0$. Knowing parameters $\lambda$ and $\alpha$ allows us to construct our model of the distribution using the Gumbel function, see equation (10).

Figure B-10
Comparison of CDF with Gumbel Function

Figure B-10 shows a comparison of our Gumbel function with $F(x)$. If our model matches closely our data plot then we can be reasonably confident in our statistical model and the probabilities we draw from it. In this case, the graph shows a reasonably good match, and the results of our statistical analysis can be used to predict the probability of there being a particular maximum depth of corrosion present in the vessel (or area of the vessel which the sample represents).

If we use the cumulative probability graph (Table B-8) this graph illustrates the probabilities of finding corrosion of a particular maximum depth. For example there is a 99.5% probability that the deepest corrosion present is 2 mm deep. Or conversely, there is a 0.5% probability of there being corrosion greater than 2 mm.

The use of this technique can be a very useful tool in the assessment of non-uniform corrosion, especially when quantitative information is needed quickly and efficiently. Extreme value statistical techniques can be used for a wide range of applications and there is good reference material available which describes the theory behind the technique and provides many examples of its application.

B.4.3 Effect of Paint

Care should be taken when applying extreme value statistical analysis to ultrasonic thickness data measured through painted surfaces. Even if the paint is well adhered, there are likely to be slight changes in paint thickness. Since the velocity of ultrasound in paint is typically 40% of the velocity through steel, a variation in paint thickness of 0.4 mm within the sample may be misinterpreted as a variation of 1 mm in steel thickness if a correction is not applied. If extreme value statistical analysis is then applied to this uncorrected data, the maximum variation in component wall thickness in the un-inspected part of the zone could then be predicted as being significantly greater than 1 mm, even if there was no corrosion or erosion and the thickness of the steel component was perfectly uniform.

Various commercially available instruments are available for measuring the thickness of paint coatings including the “banana gauge” which works on a simple magnetic principle.
B.5 Effects of Sample Size

It is important to understand whether inspection will be able to find at least one instance of any flaw present. Clearly this will depend on the population of such flaws, the effectiveness of the inspection method and the sample size. For localised cracking, spot checks are inappropriate and while sample inspections may help to determine whether a certain type of cracking mechanism is active (Ref. 26), they are unlikely to provide useful information on how many cracks are present in the zone or what their sizes are.

If a vessel zone is genuinely homogeneous, then statistical methods may be useful in determining sample size, and in extrapolating the inspection results from the sample to the whole of that zone. The confidence in the validity of sample inspections depends on the size of the sample compared to the size of the zone. The larger the sample size, the higher the confidence in the extrapolated results.

The validity of spot or sample inspections also depends on the degradation mechanism and the population of flaws present. For a zone susceptible only to uniform corrosion, a few spot checks of wall thickness may provide highly reliable information on the extent of degradation in the whole of that zone. Repeat measurements at the same locations during future inspections can then be used to assess corrosion rates.

If spot or sample checks reveal unexpected degradation, or more severe degradation than anticipated, then increased coverage (possibly up to 100%) is likely to be required.

B.5.1 Analysis Methods

Assume a weld has a uniform random distribution of flaws within its length. This random distribution can be represented as a percentage of defective weld structure. If a flaw will be detected when the region it is in is inspected (assumes 100% detection capability), the problem is to determine the probability of detecting at least 1 flaw when only inspecting a percentage of the weld volume (and therefore e.g. being alerted to the fact that a particular degradation mechanism is active)

- POI: Probability of Inclusion of a Flaw
- Cov: Percentage Coverage of the Weld Volume.
- $D_d$: Flaw Distribution as a Percentage.

To assist in calculating the POI, it is assumed that the weld volume is divided into 100 discrete units. The probability that a given unit contains a flaw is: $P_d = D_d / 100\%$.

### General Formula

\[
PON = \frac{(100 - P_d)!(100 - Cov)!}{100! (100 - Cov)!}
\]

#### B.5.1.2 Binomial Distribution:

\[
POI = 1 - PON = 1 - \left( \frac{n!}{(n-r)r!} \right) P_d^{n-r} P_0^r
\]

where:
- $n = \text{Cov}$
- $r = 0$ flaws to detect

By altering $n$ from 0 to 100% coverage the POI rises from 0 to 1 in a curve.

A more rigorous treatment, which also addresses the probability of detection (POD) of the inspection method, is provided in the reference below.
Figure B-11
Probability of Detecting 1 Defect Given a Percentage coverage of a Defective Weld.
Simple Distribution

Figure B-12
Probability of Detecting 1 Defect Given a Percentage coverage of a Defective Weld.
Using Binomial Distribution Model
Figure B-13
Probability of Detecting 1 Defect Given a Percentage coverage of a Defective Weld. Using Poisson Distribution Model