RECOMMENDED PRACTICE
DNV-RP-G101

RISK BASED INSPECTION OF OFFSHORE TOPSIDES STATIC MECHANICAL EQUIPMENT

OCTOBER 2010

DET NORSKE VERITAS

FOREWORD

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CHANGES

- **General**

As of October 2010 all DNV service documents are primarily published electronically.

In order to ensure a practical transition from the “print” scheme to the “electronic” scheme, all documents having incorporated amendments and corrections more recent than the date of the latest printed issue, have been given the date October 2010.

An overview of DNV service documents, their update status and historical “amendments and corrections” may be found through http://www.dnv.com/resources/rules_standards/.

- **Main changes**

Since the previous edition (April 2009), this document has been amended, most recently in October 2009. All changes have been incorporated and a new date (October 2010) has been given as explained under “General”.

CONTENTS

1. Introduction

1.1 Objective/Contents

The objective of this Recommended Practice is to describe a method for establishing and maintaining a risk-based inspection (RBI) plan for offshore pressure systems. It provides guidelines and recommendations which can be used to customize methods & working procedures that support the inspection planning process. It is divided into two parts covering (1) an introduction to RBI; and (2) recommendations for a working process. More detailed material is presented in the appendices.

1.2 Scope/Application/Limitations

This recommended practice is primarily intended to be used for the planning of in-service inspection for offshore topsides static mechanical pressure systems when considering failures by loss of containment of the pressure envelope. Failure modes, such as failure to operate on demand, leakage through gaskets, flanged connections, valve stem packing, together with valve passing and tube clogging are not addressed in this document.

The focus is upstream, offshore pressure systems, but with the use of the appropriate data it can be applied onshore as well. The pressure system boundaries for applicability of the methods are the Christmas tree wing valve through to the export pipeline topsides ESD valve. This involves the following types of components:

- piping systems comprising straight pipe, bends, elbows, tees, fittings, reducers
- pressure vessels and atmospheric tanks
- pig launchers and receivers
- heat exchangers
- unfired reboilers
- valves
- pump casings
- compressor casings.

Excluded from the scope of the Recommended Practice are:

- structural items including supports, skirts and saddles
- seals, gaskets, flanged connections
- failure of internal components and fittings
- instrumentation.

1.3 Relationship to Other Codes and Standards

There are a number of design codes covering pressurised equipment, and these should be sought where needed. A number of codes have also been developed regarding the assessment of fitness-for-service and remaining life, the most comprehensive being API 579-1/ASME FFS-1 [API/ASME 2007]. Such codes can be used to justify continued service when damage is found during inspection.

It should be noted that the use of risk-based principles acknowledges explicitly that it is cost-effective to allow some systems to fail as long as the consequences of that failure are sufficiently low. This also implies that some systems may have such high consequences of failure that such failure is wholly unacceptable and, therefore, these should also receive attention even when the probabilities of failure are not significantly high. Furthermore, if the chosen RBI method is based on formal probabilistic methods, taking account of uncertainties in the different parts of the risk assessments (not necessarily the probability of failure assessment), the results may be difficult to interpret intuitively.

These principles may challenge some accepted design codes based on deterministic design and fitness-for-service codes, particularly where worst-case technical scenarios are used in the calculations in combination with the absence of consequences of failure consideration. It is possible that a discrepancy in the requirements for inspection and remedial action will arise if such methods are directly compared with risk-based methods. Both cases would indicate that inspection is still required to monitor the progress of degradation, but that the timing of that inspection would be different for the deterministic and risk assessments.

Risk-based inspection methods and applications are also described in documents prepared by ASME and API. Inspection planning and execution standards and recommended practices are published by ASME [API 1998; API 2000; API 2002; API 2006; ASME 1994].

2. Abbreviations & Definitions

2.1 Abbreviations

API	American Petroleum Institute
ASME	American Society for Mechanical Engineers
ASNT	American Society for Non-Destructive Testing
CoF	Consequence of Failure
DNV	Det Norske Veritas
ESD(V)	Emergency Shut Down (Valve)
FAR	Fatal Accident Rate
FORM	First Order Reliability Method
PFD	Process Flow Diagram
PLL	Potential Loss of Life
PoD	Probability of Detection
PoF	Probability of Failure
P&ID	Piping and Utilities Diagram
QRA	Quantitative Risk Analysis
RBI	Risk-based Inspection
RCM	Reliability Centred Maintenance
UFD	Utilities Flow Diagram

2.2 Definitions

Term	Definition
Component	The individual *parts* that are used to construct a piping system or item of equipment, such as nozzles, flanges, elbows, straight pieces of pipe, tubes, shells and similar.
Condition Monitoring	*Monitoring* of plant physical conditions which may indicate the operation of given *degradation mechanisms*. Examples are visual examination of painting, corrosion monitoring, crack monitoring, wall thickness monitoring.
Confidence CoV	A quantitative description of the uncertainty in the data used in analyses, indicating the spread in the distribution of values. A data set in which the assessor has high confidence can be given a low CoV.
Consequence of Failure (CoF)	The outcomes of a *failure*. This may be expressed, for example, in terms of safety to personnel, economic loss, damage to the environment.
Consequence of Failure Ranking	A qualitative statement of the consequence of failure. Often expressed as a textual description (high, medium, low) or numerical rank (1, 2, 3).
Consequence of Failure Type	The description of consequences of failure expressed as safety, environment or economic consequence.
Corrosion Group	A group of components or parts of components that are exposed to the same internal and/or external environment and made of the same material, thus having the same potential degradation mechanisms. Groups should be defined such that inspection results made on one part of the group can be related to all the parts of the same group.
Coefficient of Variation(CoV)	The CoV indicates the spread of a distribution. The greater the CoV the greater the distribution is spread and therefore the greater the uncertainty in any value within that distribution. CoV is calculated as the standard deviation of a distribution divided by the mean value of that distribution.
Damage (type)	The observed effect on a component of the action of a *degradation mechanism*. The damage type gives rise to the *failure mechanism* of a component. Examples of damage include cracking, uniform wall thinning and pitting.
Damage Model	A mathematical and/or heuristic representation of the results of *degradation*. This may express the accumulation of *damage* over time as functions of physical or chemical parameters, and normally includes the estimation of the conditions that give rise to *failure*.
Damage Rate	The development of *damage* over time.
Degradation	The reduction of a component’s ability to carry out its function.
Degradation Mechanism	The means by which a component degrades. Degradation mechanisms may be chemical or physical in nature, and may be time- or event-driven. The degradation mechanisms covered by this Recommended Practice are: — internal and external corrosion — sand erosion — fatigue — stress corrosion cracking.
Economic Risk	An expression of the occurrence and outcome of a failure given in financial terms (units of currency per year). This is calculated as the product of the probability of failure and the financial consequences of that failure, and can include (but is not limited to) the value of deferred production, the cost of repairs to equipment and structure, materials and man-time used in repair.
Environmental Risk	An expression of the occurrence and outcome of a failure given in terms relevant to environmental damage. This may be expressed in units relevant to the installation, such as volume per year or currency per year.
Equipment	Equipment carries out a process function on offshore topsides that is not limited to transport of a medium from one place to another, and therefore comprises but is not limited to: pressure vessels, heat exchangers, pumps, valves, filters.
ESD Segment	See “Segment”.
Failure	The point at which a component ceases to fulfil its function and the limits placed on it. The failure condition must be clearly defined in its relationship to the component. Failure can be expressed, for example, in terms of non-compliance with design codes, or exceeding of a set risk limit, neither of which necessarily implies leakage. In this Recommended Practice, failure implies loss of containment.
Failure Mechanism	The means by which a component fails due to the progression of *damage* beyond the set limits imposed by the operator (such as a risk acceptance limit) or by physical limits such as a breach of the component wall.
Failure Mode	The method by which *failure* occurs. Examples are: brittle fracture, plastic collapse and pinhole leak.
Fatal Accident Rate (FAR)	*Potential Loss of Life* per 100 000 000 hours.
Hot Spot	A location on pipe or equipment where the condition being discussed is expected to be most severe. For example, a “hot spot” for microbial corrosion is an area of stagnant flow.
Inspection	An activity carried out periodically and used to assess the progression of *damage* in a component. Inspection can be by means of technical instruments (NDT) or by a visual examination.
Inspection Effectiveness	A description of the ability of the *inspection method* to detect the damage type inspected for.
Inspection Methods	The means by which *inspection* can be carried out, such as visual, ultrasonic, radiographic.
Inspection Programme	A summary of inspection activities mainly used as an overview of inspection activity for several years into the future.
Inspection Plan	Detail of inspection activity giving the precise location, type and timing of activity for each individual inspection action that is planned.
Inspection Techniques	A combination of inspection method and the means by which it is to be applied, concerning surface and equipment preparation, execution of inspection with a given method, and area of coverage.
Limit State	A mathematical description where the loss of pressure containment is calculated. This is an expression involving consideration of the magnitude of the applied loading in relation to the *ability to resist that load.*
Limit State Design	Limit state design identifies explicitly the different *failure modes* and provides a specific design check to ensure that *failure* does not occur. This implies that the component’s capacity is characterised by the actual capacity for each individual failure mode (i.e. limit state) and that the design check is more directly related to the actual *failure mechanism*.
Monitoring	An activity carried out over time whereby the amount of *damage* is not directly measured but is inferred by measurement of factors that affect that *damage*. An example would be the monitoring of CO_2 content in a process stream in relation to CO_2 corrosion.

NDT — Non-Destructive Testing. Inspection of components using equipment to reveal the defects, such as magnetic particles or ultrasonic methods.

Operator — The organisation responsible for operation of the installation, and having responsibility for safety and environment.

Potential Loss of Life (PLL) — Potential Loss of Life is expressed as the number of personnel who may lose their lives as a *consequence of failure* of a component.

Probability — A quantitative description of the chance of an event occurring within a given period.

Probability of Detection (PoD) — *Probability* that a given *damage* in a component will be detected using a given *inspection method*. PoD usually varies with the size or extent of *damage* and *inspection method*.

Probability of Failure (PoF) — The *probability* that *failure* of a component will occur within a defined time period.

Probability of Failure Ranking — A comparative listing of probability of failure for one item against another, without reference to an absolute value for probability of failure.

Process Monitoring — *Monitoring* of process conditions which may give rise to given *degradation mechanisms*. Examples are monitoring of dew point in a gas line, monitoring temperature, sand monitoring.

QRA — Quantitative Risk Assessment: The process of hazard identification followed by numerical evaluation of event *consequences* and frequencies and their combination into an overall measure of risk.

Risk — Risk is a measure of possible loss or injury, and is expressed as the combination of the incident *probability* and its *consequences*. A component may have several associated risk levels depending on the different *consequences of failure* and the different *probabilities* of those failures occurring.

Risk Acceptance Limit — Risk acceptance limits are the limits above which the operator will not tolerate risk on the installation. The risk limits can be safety related (absolute), environment related (absolute) or cost related (cost-benefit). These should be calibrated against the rest of the operators' installations and similar installations within the offshore oil and gas sector. These limits can be qualitative or quantitative and should be defined for each type of risk to be assessed.

Risk-based Inspection (RBI) — A decision making technique for inspection planning based on *risk* – comprising the *probability of failure* and *consequence of failure*.

Risk Type — Risk expressed for a specific outcome, such as safety for personnel, economic loss or environmental damage.

Safety Risk — Risk to personnel safety expressed in terms of Potential Loss of Life (PLL) per year.

Segment — A number of components forming part of the same pressure system, consisting of pipes, valves, vessels etc., which can be automatically closed-in by emergency shutdown valves. The segment defines the maximum volume of fluid or gas that can be released from that system in the event of a failure in any of the components. Some segments contain both liquid and gas which may be considered differently regarding consequence effects. Note that it is normal to assume that the ESD isolation functions on demand, but this may not be applicable to all cases.

System — A combination of piping and equipment intended to have the same or similar function within the process. This may be, for example, Instrument Air Supply, or Low Pressure Gas Compression.

Tag, Tag number — The unique identification of a part, component, pipe or equipment.

Time to Failure — The duration from a specified point in time until the component suffers *Failure.*

3. Risk-based Approach

3.1 Integrity Management Approach

An important driver that influences the performance of a production plant, like an offshore oil and gas installation, is the high utilization of the equipment. This can be achieved by minimizing the equipment downtime using reliable components, inclusion of redundant units and effective-efficient inspection-maintenance service. While meeting the high performance goals, the plant operators must also satisfy the stringent regulations in health, safety and environment (HSE). In order to successfully satisfy both of these requirements it is imperative that, under specified operating conditions, the loss of the technical integrity of the asset is kept to the minimum.

The maintenance of technical integrity comprises of all activities that investigate the extent of decline in performance of equipment and systems, take cognizance of the degradation processes and seek to prevent further degradation or, if the level or rate is unacceptable, repair or replace the degraded component (maintenance).

Figure 3-1 shows a generalised maintenance management system that is required for a systematic integrity management of an asset.

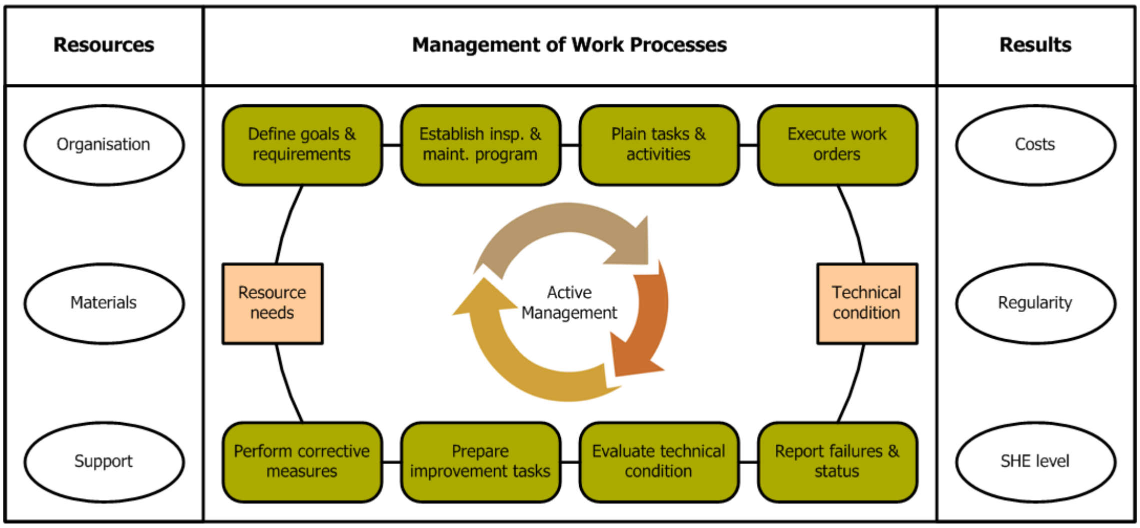

Figure 3-1
Maintenance management system

3.2 Basic Risk Management

The risk management approach is based on applying a structured approach and making the best use of the available knowledge towards assessing, mitigating (to an acceptable level) and monitoring of risks. It does this by first identifying hazards, where a hazard is anything that is a potential source of harm related to human injury, damage to the environment, damage to property or loss in production [ISO 2000]. The hazards are recorded in a hazard register (or risk register) which defines how the hazard can develop into an accident, the potential accident consequences, and the safeguards in place that provide protection from the hazard. They are then analysed for all reasonably foreseeable detrimental impacts that can have on asset integrity and reliability.

Based on the hazard analysis the associated risk is assessed. This is done by identifying possible failures, estimating the probability of failures and assessing the consequence of failures. The extent and sophistication of the assessment is dependent upon the anticipated magnitude of the risk. This generally means conducting a coarse risk assessment of all hazards and a more detailed assessment of those with the greater potential to cause harm.

The results of the risk assessment are used for taking steps to reduce the impact of failure to *as low as reasonably practicable (ALARP)*.

The risk management process is a continuous activity to reflect the changes in the operating environment and the need to monitor and maintain the performance of the resources allocated.

While carrying out the basic risk management the following should be considered:

- Risk and reliability analysis of asset performance data are used to support the assessment of opportunities for performance improvement.
- The risks to asset integrity and reliability in projects and operations are managed in accordance with good practice.
- Data on asset performance are collected and assessed as a basis for determining risk management measures.
- Appropriate performance standards for the effective management of risks to asset integrity and reliability are developed.
- A current register is maintained of actions required to restore and maintain asset integrity and reliability.
- Verification that actions to manage the risks to asset integrity and reliability are completed in a timely fashion and to an appropriate standard.

3.3 Maintenance and Inspection Planning

Having carried out the risk assessment inspection, test and maintenance activities are planned and executed according to a defined plan. The plan reflects the risk (probability and consequence) of the equipment failing and the strategy to detect, prevent, control and mitigate potential failure. The condition of equipment following inspection, test or maintenance actions is recorded and analysed and is used to update the risk-based plan. Figure 3-2 shows a generalised work process for establishing a inspection-maintenance program.

The planning of maintenance and inspection should reflect the criticality of equipment and their performance standards developed from the risk management activities. It should seek to optimise the allocation of scarce resources (people, specialist equipment, spare parts, consumables) to maintain the lifecycle value of the asset and not compromise production or HSE commitments.

3.4 Inspection

Inspection is one of the many dedicated activities within offshore management that contribute to controlling and minimising offshore risks. The role of inspection is to check/confirm whether degradation is occurring, to measure the progress of that degradation, and to help ensure that integrity can be maintained. It provides assurance that asset integrity is maintained in accordance with the design intent.

Some important points to note about inspection are:

- Inspection activities provide specific, relevant, accurate and timely information to management on the condition of assets.
- Inspection activity is planned and executed with due regard for the policy and the risks to its achievement.
- Threats to asset integrity are identified sufficiently early so that they can be remedied cost effectively with no appreciable impact on asset integrity or safety.
- The asset register is maintained current with the condition of assets and their inspection history.
- Inspection activity is scheduled to provide the necessary level of assurance of the condition of plant and equipment while also minimising the detrimental impact on production operations.
- Equipment is handed over from operations to inspection personnel prior to inspection activity, and from inspection to operations personnel following inspection activity in accordance with a formal procedure which ensures that appropriate information on the condition of the equipment is exchanged.
- Inspection activity is subject to appropriate verification of its performance.

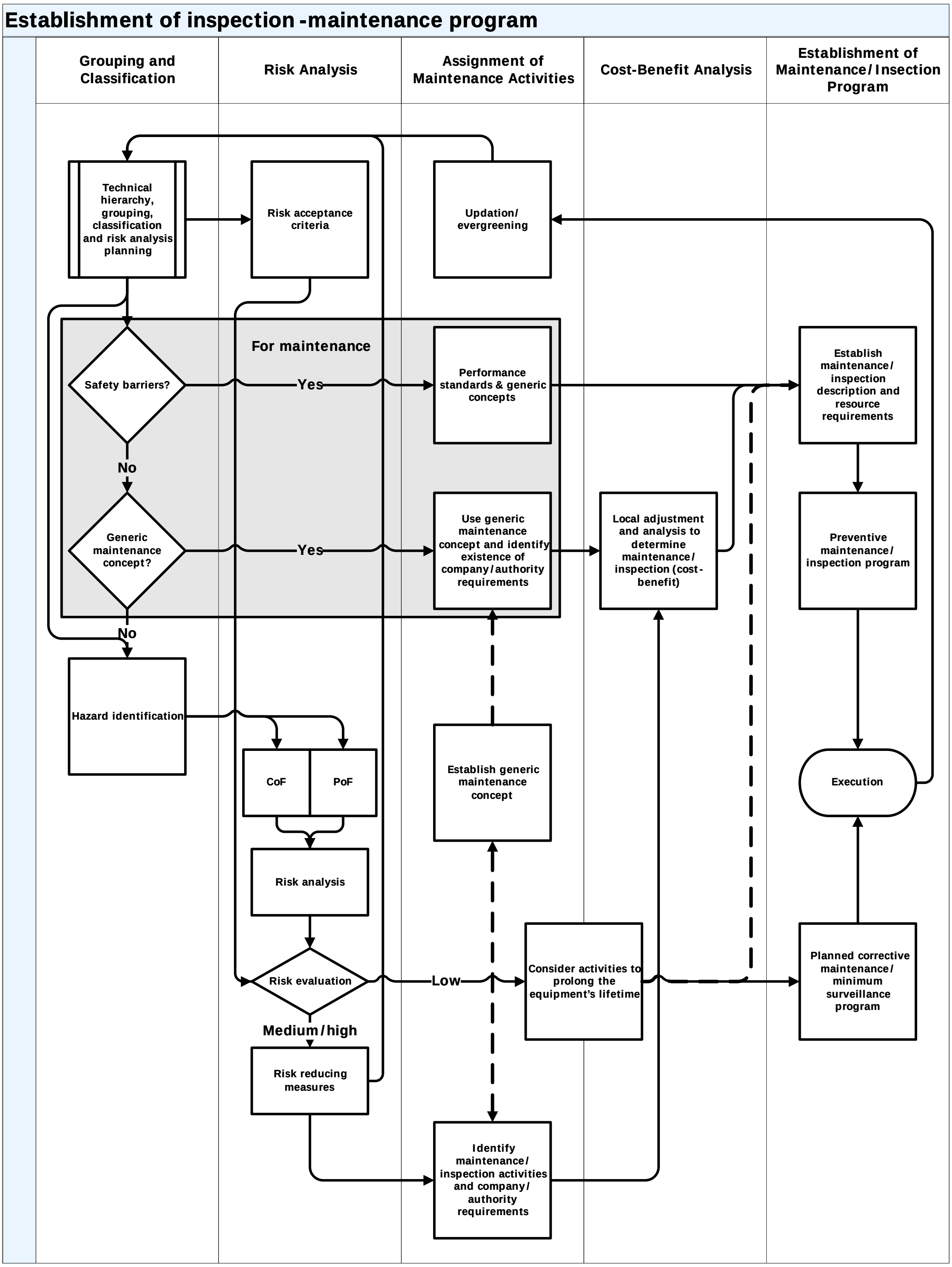

Figure 3-2
Work process for the establishment of inspection-maintenance program

3.5 Risk-based Inspection (RBI)

Risk-based Inspection (RBI) is a decision making technique for inspection planning based on *risk* – comprising the *consequence of failure (CoF)* and *probability of failure (PoF)*. It is a formal approach designed to aid the development of optimised inspection, and recommendations for monitoring and testing plans for production systems. It provides focus for inspection activity, to address explicitly the threats to the integrity of the asset and its capability to generate revenue through production. Figure 3-3 shows the deliverables of an RBI assessment to the inspection program.

RBI is carried out for piping and vessels, including heat exchangers, tanks, pressure vessels, and filters. The scope of the RBI encompasses all pressure systems in the plant, whether hydrocarbon-containing or utility.

To carry out the RBI analysis for each item, the consequences of failure (CoF) and probability of failure (PoF) are assessed separately. The two are then combined to obtain risk of failure. This evaluation is carried out separately for *Safety* (addressing personnel death and injury), *Environmental* (addressing damage to the environment) and *Economic* (addressing financial loss).

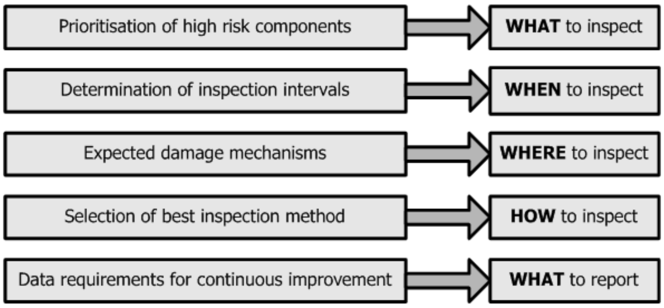

Figure 3-3
Deliverables of an RBI assessment to the inspection program

3.6 Motivation for Using RBI

Reasons for selecting a risk-based approach to inspection planning are:

— A systematic overview of the installation is achieved together with an explicit, systematic and documented breakdown of the installation's risks clearly showing the risk drivers and recommending appropriate actions.
— Inspection efforts are focused on items where the safety, economic or environmental risks are identified as being high; whilst similarly the efforts applied to low-risk systems are reduced.
— Probabilistic methods can be used in calculating the extent of degradation and hence allow variations and uncertainties in process parameters, corrosivity, and thus degradation rates and damage extent, to be accounted for.
— Consequences of failure are considered, so that attention can be focused where it will have significant effect. If there are significant uncertainties in the outcomes, these can be modelled by investigating the probabilities of the various outcomes using an event tree approach.
— Contributing in a pro-active and focused manner to ensuring that the overall installation risk does not exceed the risk acceptance limit set by the authorities and/or operator.
— Identifying the optimal inspection or monitoring methods according to the identified degradation mechanisms and the agreed inspection strategy.

3.7 Inspection Planning

The inspection planning judiciously allocates resources to carry out efficient and effective inspection to accurately determine the condition of the plant. This involves balancing the cost of inspection, including the necessary downtime, against the benefits of inspection, including the effectiveness of that inspection. The inspection planning process comprises of three parts:

1) *Risk Based Inspection Analysis* – It helps to decide (a) parts of the plant that should be inspected; (b) degradation mechanism that should be considered; (c) level of inspection that should be carried out; and (d) the time when the inspection should be carried out.

2) *Development of an Inspection Frame Programme* – It helps to develop an outline of the expected inspections with a long-term view of the future. This incorporates the RBI findings as well as experience and judgement related to the degradation that is not included in the RBI.

3) *Detailed Inspection Plan* – It is done by interpreting the findings of the RBI analyses and other plant experience to develop a precise plan. The plan should cover (a) type and technique of inspection; (b) preparation required; (c) the necessary inspection coverage; and (d) level or quality of inspection.

4. Risk-based Inspection – Overview

4.1 Introduction

Figure 4-1 illustrates the basic RBI concept. RBI is a systematic effort to try to understand both sides of the figure in order to plan inspection.

On the left side of the figure, the key concept is the degradation mechanism concept based on defined scenarios. This RP concentrates on the most common ones where inspection and/or monitoring efforts can be used to manage the associated risks. These degradation mechanisms are introduced in Appendix A and Appendix B.

Each of the different degradation mechanisms may or may not lead to loss of containment. The probability of failure (loss of containment) can be estimated numerically, if any degradation model exists, or by means of engineering judgement. More detailed recommendations regarding the assessment of these degradation mechanisms and associated failure probabilities are given in Appendix A and Appendix B.

Given that loss of containment has occurred, the potential consequences will depend very much on the size of the hole – which can vary between a pinhole to a full bore rupture. This RP uses a fixed template with four potential hole sizes, and these are presented in Appendix A.4. For each of the degradation mechanisms, this RP provides recommendations as to the expected distribution of hole sizes. This information should be taken into account when considering the potential effect and consequences of any loss of containment; and can potentially materially affect the outcome.

Given a loss of containment, the consequences need to be assessed. Whether or not the loss of containment can lead to ignition or pollution is an important issue. A general introduction to some consequence assessment principles are presented in Appendix C, together with some end consequence descriptions and guidance.

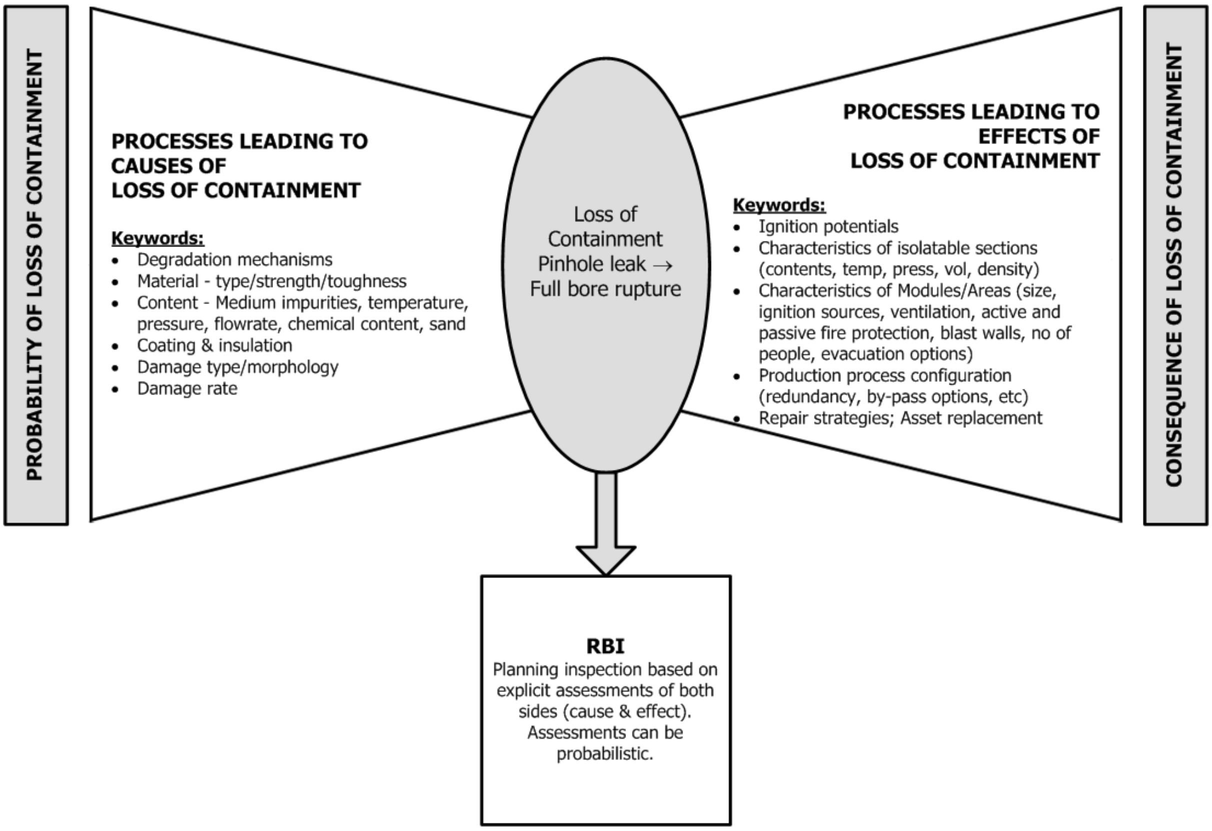

Figure 4-1
RBI basic concept

4.2 RBI Methods

Risk-based inspection can be carried out using methods that are qualitative or quantitative. In practice, most risk-based inspection efforts are carried out using a blend of both the methods and, hence, called semi-quantitative method.

4.2.1 Quantitative

Quantitative model can be interpreted as *model-based approach* in which where suitable models are available, a numerical value is calculated. Quantitative values can be expressed and displayed in qualitative terms for simplicity by assigning bands for probability of failure and consequence of failure, and assigning risk values to risk ranks.

The advantage of the quantitative approach is that the results can be used to calculate with some precision, when the risk acceptance limit will be breached. The method is systematic, consistent and documented, and lends itself to easy updating based on inspection findings. The quantitative approach typically involves the use of a computer to calculate the risk and the inspection programme. This can be initially data-intensive, but removes much repetitive detailed work from the traditional inspection planning process.

4.2.2 Qualitative

Qualitative model can be interpreted as *expert judgement-based approach* in which a numerical value is not calculated and assigned, but instead a descriptive ranking is given, such as low, medium or high, or a numerical ranking such as 1, 2 or 3. Qualitative ranking is usually the result of using an engineering judgement-based approach to the assessment.

The advantage of using a qualitative approach is that the assessment can be completed quickly and at low initial cost, there is little need for detailed information, and the results are easily presented and understood. However, the results are subjective, based on the opinions and experience of the RBI team, and are not easily updated following inspection. It is not easy to obtain results other than a ranking of items in terms of risk; the variation of risk with time allowing estimation of inspection interval based on the risk acceptance limit is not possible.

4.2.3 Semi-quantitative/Semi-qualitative

Methods are said to be semi-quantitative or semi-qualitative in the following cases:

— Parts of the RBI assessment are carried out using qualitative methods. For example:

  — the CoF assessment is qualitative and the PoF assessment is quantitative
  — the CoF and PoF assessments are quantitative, whereas the risk ranking and time to inspection assessment are qualitative.

— Assignment of PoF and/or CoF categories is done by simple algorithms based on a chosen set of most relevant parameters.
— Assignment of PoF and CoF is made by engineering judgement.

4.3 Degrees of Quantification

The following three degrees of quantification can be used:

— quantitative
— qualitative
— semi-quantitative / semi-qualitative.

As mentioned earlier in Section 4.2, most risk-based inspection efforts are carried out using a blend of these different methods. The following are some recommendations with regard to degrees of quantification.

1) The RBI Screening Assessment (Section 5.8) should be a qualitative assessment. Guidance is given in Appendix E.
2) If the RBI Detailed Assessments are carried out in a qualitative manner:

   a) This should be done in the form of work sessions.
   b) Separate sessions should be organised for the degradation mechanisms assessment, CoF assessment, PoF assessments, and risk and inspection scheduling assessments.
   c) Sessions should be carried out at Level 2.
   d) Each of these assessments should have their own set of assessment forms similar to the screening form in Appendix E. Guidance and prompt questions should also be established in a similar way.
   e) The set of assessment forms for degradation mechanisms should comprise as a minimum three separate forms for each of the three groups:

      — internal degradation mechanisms
      — external degradation mechanisms
      — mechanical damage.

      Preferably, the set should include a separate form for each individual degradation mechanism.
   f) Same principle applies for the different consequence types being assessed.
   g) Risk matrices with decision procedures should be developed, agreed on and presented to all involved personnel prior to the work sessions.
   h) Qualified senior personnel (10 years of experience or more) should be included in all sessions.
   i) A qualified senior RBI engineer from outside the group (either an external consultant or an engineer from another part of the organisation) should attend the sessions in order to ensure QA verification.
   j) When the PoF assessment is qualitative:

      — Generally, numerical values/ranges should not be assigned. Only highly qualified personnel should be allowed to assign numerical values/ranges based on a qualitative assessment based on engineering judgement.
      — Generally, the risk assessment should be qualitative. If a numerical value/range has been assigned based on a qualitative PoF assessment, a quantitative risk assessment can be carried out (given a quantitative CoF assessment).

   k) When the safety CoF is qualitative, numerical values/ranges should not be assigned.

3) If the RBI Detailed Assessments are carried out in a quantitative manner:

   a) Quantitative probability of failure values have a wide range from zero to unity, and therefore a logarithmic scale is recommended for displaying the results graphically.
   b) A cut-off point is set for PoF below 10^{-5} as probabilities below this number are both very difficult to model and observe, and will usually represent an insignificant risk.
   c) Safety consequence should be expressed in terms of Potential Loss of Life (PLL) for personnel.
   d) Economic consequence should be expressed in financial terms using appropriate currency units.
   e) Environmental consequences can be expressed in terms of mass or volume of a pollutant released to the environment, or in financial terms as the cost of cleaning up the spill, including consideration of fines and other compensation.
   f) The consequence scale used in matrices and other presentations is necessarily different for PLL and currency, and should be selected to account for the full range of values.
   g) The consequence of failure scale should advance in decades for each category, where the lowest category includes values up to the risk acceptance limit assuming that probability of failure ≈ 1.0.

4) When both quantitative and non-quantitative methods are being used for a certain type of assessment, it is recommended to revisit and calibrate the non-quantitative assessments once the quantitative assessments are finalized.
5) Semi-quantitative / semi-qualitative methods based on simplified algorithms should be qualified by either external consultants/engineers or engineers from another part of the organisation.
6) It is an advantage to use a qualitative approach if there is little well-documented detailed information.
7) In the cases where the team has considerable general experience and much experience for the specific installation(s) being assessed, it may be more efficient to choose a qualitative approach for the RBI Detailed Assessment even if documentation is of good quality. In such cases, an underlying assumption is that the people involved will be available for future assessments and that the process has been sufficiently documented.

4.4 Probability of Failure (PoF)

Probability of failure (PoF) is the probability of an event occurring per unit time (e.g. annual probability). It is estimated on the basis of the component degradation. PoF is related to the extent of, and uncertainty in, the degradation related to the component's resistance to its loading.

Quantitative probability of failure values have a wide range from zero to unity, and therefore a logarithmic scale is recommended for displaying the results graphically.

The recommended probability of failure scale used in the context of this recommended practice is as shown in Table 4-1. The table also shows the recommended qualitative ranking scale assigned to the quantitative probability of failure values.

Table 4-1 Probability of failure description

Cat.	*Annual failure probability*		*Description*	
	Quantitative	*Qualitative*		
5	$> 10^{-2}$	Failure expected	(1)	In a small population*, one or more failures can be expected annually.
			(2)	Failure has occurred several times a year in location.
4	10^{-3} to 10^{-2}	High	(1)	In a large population**, one or more failures can be expected annually.
			(2)	Failure has occurred several times a year in operating company.
3	10^{-4} to 10^{-3}	Medium	(1)	Several failures may occur during the life of the installation for a system comprising a small number of components.
			(2)	Failure has occurred in operating company.
2	10^{-5} to 10^{-4}	Low	(1)	Several failures may occur during the life of the installation for a system comprising a large number of components.
			(2)	Failure has occurred in industry.
1	$< 10^{-5}$	Negligible	(1)	Failure is not expected.
			(2)	Failure has not occurred in industry.

Notes:
* Small population = 20 to 50 components.
** Large population = More than 50 components

Table 4-2 Consequence of failure qualitative ranking scales [ISO 2000]

Rank	*CoF Personnel Safety*	*CoF Environment*	*CoF Economic*
A	Insignificant	Insignificant	Insignificant
B	Slight/minor injury	Slight/minor effect	Slight/minor damage
C	Major injury	Local effect	Local damage
D	Single fatality	Major effect	Major damage
E	Multiple fatalities	Massive effect	Extensive damage

4.5 Consequence of Failure (CoF)

Consequence of failure is evaluated as the outcome of a failure given that such a failure will occur. It is defined for the three consequence types: Personnel Safety, Environment and Economic.

— *Safety consequence* should be expressed in terms of potential loss of life (PLL) for personnel.
— *Economic consequence* should be expressed in financial terms using appropriate currency units.
— *Environmental consequences* can be expressed in terms of mass or volume of a pollutant released to the environment, or in financial terms as the cost of cleaning up the spill, including consideration of fines and other compensation.

It is generally recommended that consequence of failure values or rankings be assessed and presented separately depending on the consequence type. This allows each type to be addressed and given proper focus. This is especially important when using quantitative methods where it is not recommended to combine/mix personnel safety and economic consequences.

An example of qualitative and quantitative ranking scales which can be used for the consequence of failure are shown in Table 4-2 and Figure 4-2 [ISO 2000].

4.6 Estimation of Risk

The risk associated with a failure from a given degradation mechanism is estimated as the combination of the probability of failure and the consequence of failure. The probability and consequence of failure can be estimated in either a qualitative or quantitative manner, or by using a combination of qualitative and quantitative methods.

The risk can be presented as a matrix. This allows the relative contribution of both factors to be seen (Consequence of Failure and Probability of Failure). While the matrix is a static picture of risk calculated for any one time period, but matrices can be prepared for different parts of the time period to illustrate development of risk.

Separate matrices for each risk type are recommended, especially when quantitative methods are used. The matrix should be standardised for each operator/field in order to simplify communication and the decision process. To achieve adequate resolution of detail, a 5 × 5 matrix is recommended.

It is recommended that the results are checked for the validity of any assumptions that were made during the assessments, the correctness of data used, and that the risk outputs are broadly in agreement with those given in any relevant safety case, QRA or similar documentation. Notice that QRA / Safety cases studies and RBI studies have different objectives, and hence utilise somewhat different data and equations. Consequently, it is likely that results from the different studies will not be in exact agreement.

An example of a qualitative assessments matrix based on ISO 17776 is shown in Figure 4-2 [ISO 2000]. The matrix has probability of failure on the vertical axis, and consequence of failure on the horizontal. The divisions between the categories of each should be chosen taking into consideration the absolute magnitude of the values & their ranges (relevant for quantitative assessments), and the need for consistent reporting when comparing different installations.

The risk matrix shows three risk levels, identified through colour:

— *Green - Low risk* - Risk is acceptable. Generally, action needs to be taken to ensure that risk remains within this region; typically this involves operator round, cleaning, general visual inspections (GVI) to confirm that there have been no changes in equipment condition.
— *Yellow - Medium risk* - Risk is acceptable. Action (such as NDT, functional tests and other condition monitoring activities) should be taken to measure extent of degradation so that action can be taken to ensure risks do not rise into the red high-risk region.
— *Red - High risk* - Risk level is unacceptable. Action must be taken to reduce probability, consequence or both, so that risk lies within the acceptable region.

PoF Ranking	PoF Description	A	B	C	D	E
5	(1) In a small population, one or more failures can be expected annually. (2) Failure has occurred several times a year in the location.	YELLOW	RED	RED	RED	RED
4	(1) In a large population, one or more failures can be expected annually. (2) Failure has occurred several times a year in operating company.	YELLOW	YELLOW	RED	RED	RED
3	(1) Several failures may occur during the life of the installation for a system comprising a small number of components. (2) Failure has occurred in the operating company.	GREEN	YELLOW	YELLOW	RED	RED
2	(1) Several failures may occur during the life of the installation for a system comprising a large number of components. (2) Failure has occurred in industry.	GREEN	GREEN	YELLOW	YELLOW	RED
1	(1) Several failures may occur during the life of the installation for a system comprising a large number of components. (2) Failure has occurred in industry.	GREEN	GREEN	GREEN	YELLOW	YELLOW
CoF Types	Safety	No Injury	Minor Injury Absence < 2 days	Major Injury Absence > 2 days	Single Fatality	Multiple Fatalities
	Envirnoment	No pollution	Minor local effect. Can be cleaned up easily.	Significant local effect. Will take more than 1 man week to remove.	Pollution has significant effect upon the surrounding ecosystem (e.g. population of birds or fish).	Pollution that can cause massive and irreparable damage to ecosystem.
	Business	No downtime or asset damage	< € 10.000 damage or downtime < one shift	< € 100.000 damage or downtime < 4 shifts	< € 1.000.000 damage or downtime < one month	< € 10.000.000 damage or downtime one year
CoF Ranking		A	B	C	D	E

Figure 4-2
Example of risk matrix [ISO 2000]

The risk assessment can be implemented using:

— risk prioritisation methods: rank equipment and systems in terms of risk magnitude, and address the highest risk equipment first, and/or
— risk acceptance limit methods: estimate risk per equipment and its change with time, and address equipment where risk will soon cross risk acceptance limit first.

5. RBI Assessment – Recommended Working Process

5.1 Introduction

This section presents an overview of a recommended RBI work process. Material presented in this section together with the material presented in the appendices can be used to further develop and customize the RBI assessment working processes.

It is important to emphasize that the basic/generic RBI process presented in this section can be applied to different levels, from installation level down to inspection point level. In order to manage the complexity of the task of planning inspection for a topsides installation, it is recommended to apply a top down approach taking care in choosing appropriate combinations of qualitative and quantitative methods. Section 5.3 covers assessment levels of detail before the rest of the section continues the presentation of the recommended RBI working process.

5.2 Basic/Generic RBI Working Process

The basic/generic risk-based inspection process is presented in Figure 5-1.

The working process has been divided into five stages:

1) Information Gathering
2) Screening Assessment
3) Detailed Assessment
4) Planning
5) Execution and Evaluation.

The RBI assessment should be reviewed on a regular basis, and revised as necessary to account for any significant changes in the input information, e.g. in process and operational data, new design conditions, changes in field economy. For most offshore processing systems the operational conditions are subject to both short-term and long-term changes due to operational practices and reservoir characteristics. It is essential to track such changes and to take appropriate actions based on these. Some changes can be anticipated, such as a tie-in to new well of different composition.

5.3 Level of Detail

Before beginning the evaluations, the (assessment/equipment) level of detail at which evaluations are to be carried out should be established and agreed. This should account for the level of detail required by the inspection planners (who are to work with the results of the assessment), as well as the amount and level of input data available. The equipment level hierarchy can be useful in connection with making choices as to how the inspection planning process is to be defined and specified. The level of detailing may be increased for the high-risk items. The assessment process may, for example, start at Level 0 resulting in high level plans for a number of installations, and proceed to systems level for certain individual installations and move on all the way down to part level for selected items.

It should be noted that inspection planning is concerned with the smallest level of detail (inspection point) and so if the RBI assessment is carried out at a higher level, more time will be used in the final inspection planning process than if the RBI is executed either directly at a more detailed level, or in a manner that can be easily transferred to such a level.

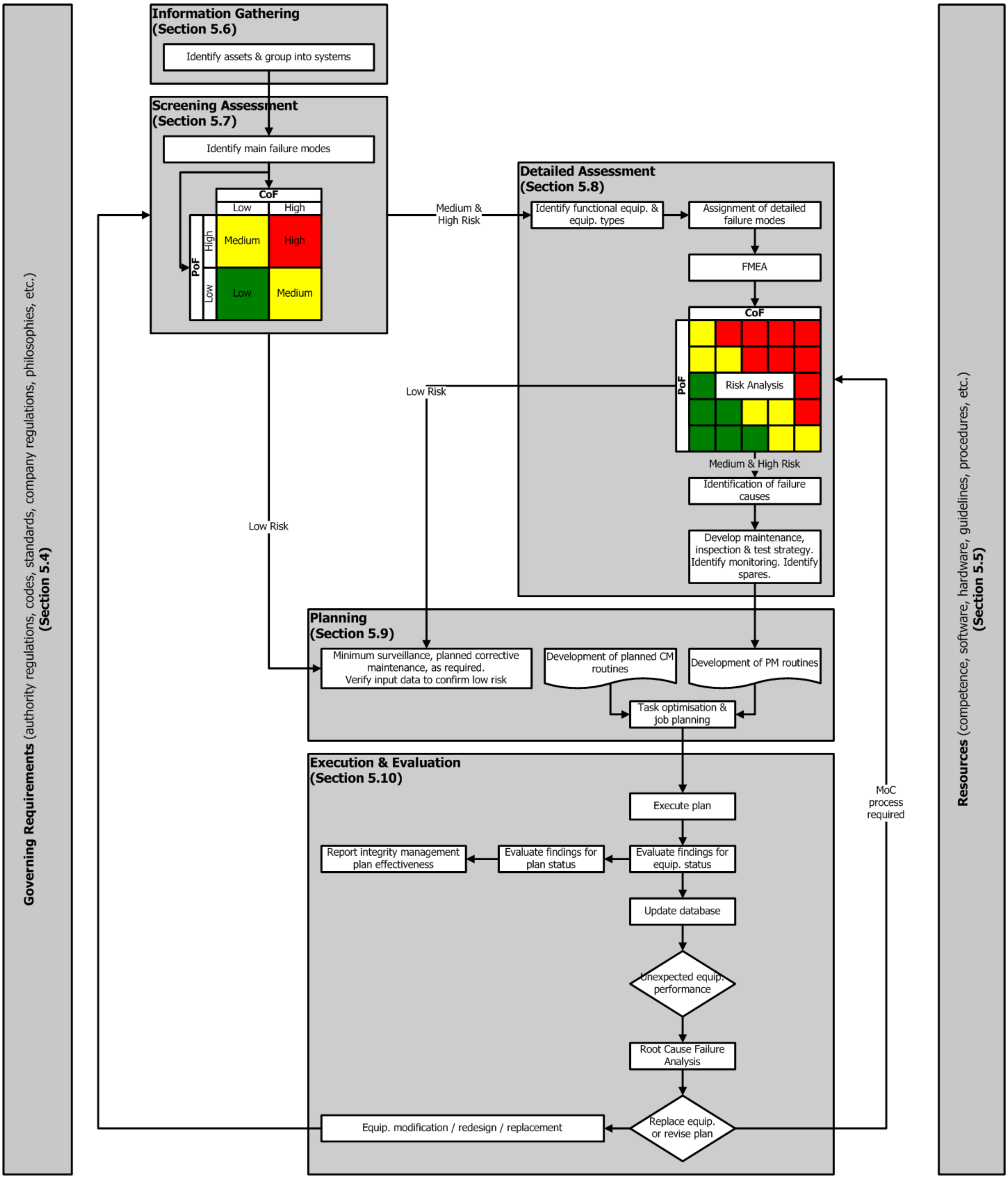

Figure 5-1
Generic RBI process

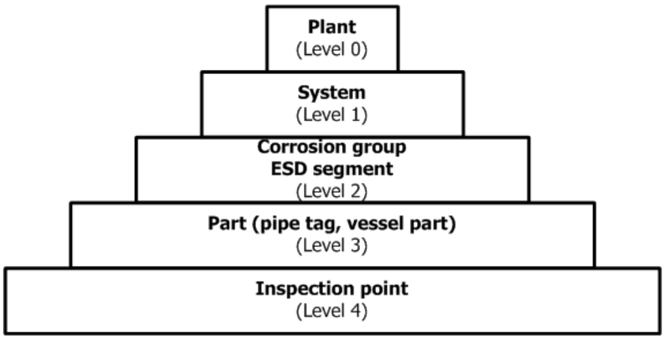

Figure 5-2
Equipment level hierarchy

Figure 5-2 shows the various equipment level hierarchy that can be used. Comments/guidelines to the different levels are presented below:

Level 0: *Level 0 refers to the plant/installation level.* An assessment at Level 0, taking into account a number of plants, can be useful to carry out in connection to, for example, budget prioritisations and distributions. Such an assessment is assumed to be carried out based on high level information. Examples of such information are: number of people on installations, location of installations, production numbers, historical information regarding availability, production interruptions related to failures by loss of containment, types of materials used on installations, presence of H_2S, CO_2 and sand on installations. An assessment at Level 0 lends itself to both qualitative and quantitative evaluations. It is very likely that the team carrying out such an assessment will be able to use engineering judgement and evaluate most aspects in a qualitative manner. Level 0 is not covered any further in this Recommended Practice.

Level 1: *Level 1 refers to the system level.* Examples of systems are the Separation and Stabilization System, the Metering System, the Closed Drain System, the Open Drain System and the Flare System. Carrying out an assessment at this level for the purpose of directly producing an inspection plan is not usual. An assessment at Level 1 is normally used to identify the systems that are judged to significantly contribute to the risk levels of the installation in question. Further assessment efforts at lower levels can be focused on these systems, whereas the remaining systems can be considered for other types of maintenance activities. An assessment at Level 1 is recommended to be carried out in a qualitative manner.

Level 2: *Level 2 refers to the corrosion group and/or ESD segment level.* An assessment at Level 2 is used to identify groups at a level which is beginning to become more meaningful and practical from an inspection plan point of view. It is important to define groups of components so that the assessment for one component can be applied to all the others within that group. Grouping is typically carried out with reference to PFDs and P&IDs. It is likely that different groups will be defined for the assessment of probability of failure (e.g. different types of corrosion groups) and consequence of failure (e.g. ESD segments). Unlike an assessment at Level 1, an assessment at Level 2 can be significantly time-consuming (the first time it is carried out). One of the main reasons for this is that the definitions of such groups are normally never readily available and are therefore often generated manually.
An assessment at Level 2 can be carried out in both a qualitative and a quantitative manner. Once these groups are in place, it is possible to either carry out the assessments based on representative cases of the groups and transfer the results to Level 4 for planning of inspection points, or continue through Level 3 by linking parts to groups and adjust assessments based on more detailed part information.
When working at this level, it is recommended to plan the work based on well-defined, manageable parts of the installation (preferably system by system – Level 1).

Level 3: *Level 3 refers to the pipe tag / vessel part level.* An assessment at Level 3 is used to develop an inspection plan and is normally based on transferring results from a Level 2 assessment down to a part level. It may be relevant to analyse certain specific parts, but a separate assessment of every part at this level is not practical. A good line list is necessary in order to carry out an assessment at this level. For the same reasons as mentioned above, an assessment at Level 3 can be time-consuming. Line lists do not normally have links to the groups from the Level 2 assessment, so this has to be done manually.

An assessment at Level 3 is dependent on a good electronic line list and good software support. Assuming that the line list is complete and of a good enough quality, the advantages of carrying out a Level 3 assessment are that:

- All sizes of the part and materials are considered.
- It is more unlikely that parts will be overlooked.
- All parts of the vessel/tag are considered.
- It allows unusual cases, and well understood equipment and degradation mechanisms to be included separately.
- Identification of high-risk parts of the vessel may save intrusive inspection.
- Separate degradation mechanisms found in specific locations in the vessel/tag are evaluated separately.
- Greatest precision in updating assessment with inspection findings may be achieved.

When working at this level, it is recommended to plan the work based on well-defined, manageable parts of the installation (preferably system by system and group by group).

Level 4: *Level 4 refers to the inspection point level.* RBI assessments at Level 4 are only carried out for inspection points of special concern. Results from assessments at Level 2 and/or Level 3 are usually transferred down to this level where inspection points are identified and chosen in isometric drawings.
When working at this level, it is recommended to plan the work based on well-defined, manageable parts of the installation (preferably system by system and group by group).

5.4 Governing Requirements

Constraints and control mechanisms in the form of different governing documents, like maintenance and inspection philosophies, as well as regulatory requirements should also be available to the RBI team. Risk Acceptance Limits are typically derived from such documents.

5.5 Resources

5.5.1 Competence/Personnel

RBI assessment and inspection planning is a multidisciplinary activity, and the following qualified and experienced personnel should be involved:

- Inspection engineers with hands-on experience of inspection of piping, pressure vessels, heat exchangers, both in-service and during construction.
- Materials/corrosion personnel with expertise in materials selection, corrosion monitoring and control, chemical treatments, fitness-for-service assessments, coatings and linings.
- Safety/consequence personnel with experience in formal risk assessment covering personnel safety, economic and environmental disciplines.
- Plant operations and maintenance personnel with detailed knowledge of the installation to be analysed.

Furthermore, successful implementation of RBI requires competent personnel carrying out the different roles and responsibilities within the inspection discipline as a whole. Communication of results from the RBI assessment team to the inspection planning team is critical. Experience has shown that close co-operation between the RBI analysis team and the inspection planning team has been a very important success factor. Ideally, these two teams should be completely integrated.

5.5.2 Roles and Responsibilities

The roles and responsibilities are organised differently by the different operator companies, but in general the activities can be split into the following tasks:

- Inspection Management
  - overall planning of the inspection activities
  - co-ordinating the inspection activities with the maintenance and operations superintendents
  - hiring any necessary inspection consultant competence and resources to serve, accommodate, and maintain the inspection system
  - supervising the inspection activities
  - co-ordinating laboratory services, material testing, sampling, etc.
  - providing quality assurance of the inspection activities
  - documenting and reporting of inspection findings and results
  - ensuring that experience feedback is used for annually updating the scope and plan for future inspections
  - evaluation of the plant condition
  - maintaining and improving the inspection system.
- Inspection Planning
  - establishing framework inspection programmes
  - establishing detailed inspection programmes
  - co-ordinating inspectors, equipment and performing other logistic services related to inspection execution
  - up-date inspection programmes based on inspection results and changes of operational parameters
  - gathering necessary documentation and information to optimise the inspection programme
  - documentation and reporting of inspection activities
  - evaluation of the plant condition.
- Assisting in RBI assessments
  - inspection execution & reporting
  - managing and performing inspection work
  - supervising NDT Operators
  - making first-hand evaluation on the inspection site
  - reporting to inspection management
  - obtaining work permits relevant to inspection activities
  - performing quality assurance on the work of inspection
  - performing non-destructive testing (NDT)
  - reporting completed testing to the senior inspector.

Requirements for inspection execution are handled by the inspector qualification schemes, such as those in accordance with ASNT requirements, and the European standard EN 473. Requirements for in-service inspection personnel covering the whole process from management through to execution, reporting and evaluation must be defined.

5.5.3 Procedures/Tools/Technology

Implementation of RBI requires appropriate procedures and/or software tools.

It is an advantage to have well documented company RBI working procedures before committing to, or developing software solutions. Such working procedures should be part of the basis for software specification/customization. It is also an advantage to specify the data management needs when choosing or developing software solutions. This can be done by specifying and maintaining a conceptual information schema.

5.6 Information Gathering (Input)

Typical examples of input sources for carrying out the RBI evaluations are:

- line list
- equipment list
- system descriptions manual
- engineering numbering system
- equipment data and vessel sheets
- piping data sheets
- layout drawings, Process Flow Diagrams (PFDs), Utilities Flow Diagrams (UFDs), Piping and Instrumentation Diagrams (P&IDs), Process and Safety Diagrams (PSDs)
- Design, Fabrication and Installation (DFI) resume
- inspection/failure/replacement details
- inspection/failure/replacement history knowledge
- corrosion protection philosophy
- material design specification and selection report
- coating specifications
- insulation specifications
- Quantitative Risk Analysis (QRA)
- design accidental load analysis
- ESD logic diagrams
- mass balance sheets
- production data (past and future)
- key operation and maintenance personnel.

In the absence of such information, assumptions may be based on judgement and experience. All such assumptions should be recorded. In case sufficient information is not available then the use of RBI should be avoided.

Three main groups define the input data needs for carrying out the risk-based analysis used as input to inspection planning:

- inspection data
- consequence data
- engineering/process data.

Some effort should be put in to understanding the sources of information and streamlining the interfaces to these sources.

- *Inspection data* – Specifications should be made for what is expected back from inspection activities in order to satisfy the models used in the analysis. Each degradation mechanism should have its own specification. Furthermore, procedures should be described for updating calculations. These procedures should include what kind of statistical analyses need to be carried out, and how.
- *Consequence data* – Specifications should be made for what is expected from quantified risk analysis reports. Safety consequence results from such analyses should be reported in such a way that is ready to use for inspection planning purposes. The challenge of transferring the results to a detailed level (e.g. pipe tag) can be solved by specifying requirements to the engineering disciplines that generate line lists, P&IDs, PFDs, etc. The link between low level components and higher level groupings should be documented in a way that eases the inspection planning work. This might also be the case for information regarding economic consequence.
- *Engineering/process data* – Basic input data, such as dimensions, pressure, temperature, can also be difficult to manage, and will depend on the quality of the interfaces to the engineering and operation disciplines that generate this information.

5.7 Screening Assessment

The purpose of the screening process is to identify, at a higher level (typically Level 2 and upwards), the elements that are judged to make a significant contribution to the risk levels. This ensures that further data gathering and assessment efforts can be focused on these elements. Given an installation, screening is typically carried out in a qualitative manner that involves identification of risk on a system by system, group by group, or major equipment item basis. On the basis of knowledge of the installation history and future plans and possible components' degradation, the consequence of failure and probability of failure are each assessed separately to be either “significant” or “insignificant” (resulting in “high”, “medium” and “low” risks), as seen in the matrix given in Appendix E.

Generally, low risk items will require minimal inspection supported by maintenance. Medium and High-risk items will require a more detailed evaluation which is the subject of the second stage of the working process. Inspection data is used only as general guidance, as the screening is intended to identify systems, groups and equipment where it is cost-effective to use more time-consuming detailed assessment. More guidance on RBI screening is given in Appendix E.

5.8 Detailed Assessment

The elements with medium and high risk from stage one (RBI screening) are the elements that need to be considered in more detail – i.e. broken down to lower levels and evaluated with either qualitative, quantitative or semi-quantitative methods. The objectives of this stage of the assessment are to identify the relevant degradation mechanisms, estimate the extent of damage, estimate when inspection should be carried out, and propose what inspection technique should be used to ensure acceptable risk levels. It is recommended to work at Level 2 (corrosion groups / ESD-segments) and transfer results down to Level 3 and/or Level 4.

Figure 5-3 shows the flowchart for carrying out detailed RBI analysis.

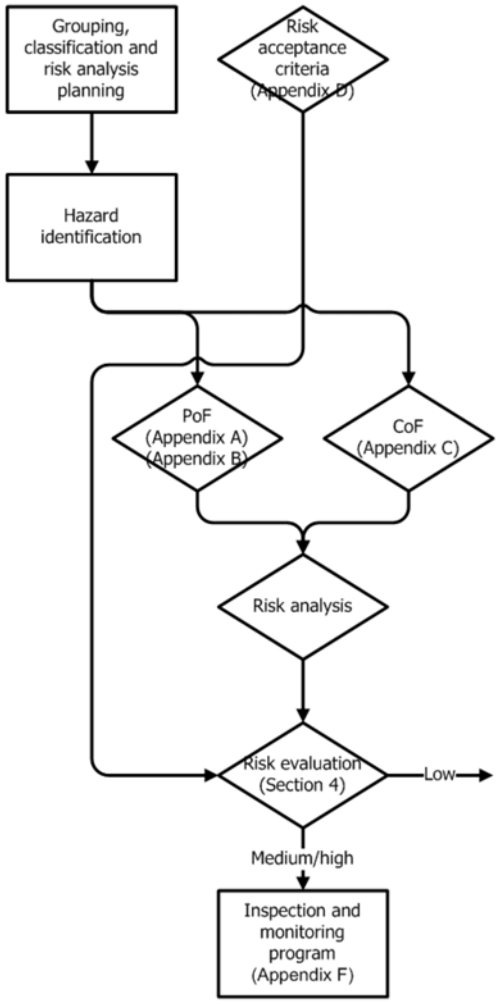

Figure 5-3
Detailed RBI assessment working process

5.9 Planning

In many cases the results of the RBI screening and detailed assessments are used as input to the final inspection planning stage, where a different team of planners works at the inspection point level and may take into account other factors and also consider logistics before finalising the plan.

The interaction between the planners and the RBI analysts may result in more refined RBI assessments carried out for certain parts and/or inspection points. Guidance on inspection planning is given in Appendix F.

This assessment provides a preliminary inspection plan, including inspection methods and timings that are readily updated as inspection data becomes available. A final executable inspection plan will normally be developed based on this preliminary plan, but also considering:

- Logistics, including available bed space, available personnel, need for specialised equipment.
- Need for interaction with maintenance activity.
- Release for inspection by operations personnel, including extent of shutdowns necessary.
- Database setup, capabilities and equipment hierarchy and possibly other factors that have not been covered by the RBI assessment.

The results from this part of the assessment provide the basis for the final detailed inspection planning. A report must be focused on the needs of the inspection planner. Typically, the report will comprise the risk results collated with any intermediate calculations related to part and process data. Additional consideration should be given to the data requirements and capabilities of any inspection planning tools that are used.

The assessment and underlying assumptions should be documented, together with a combination of the following information/data, as required, related to each item:

— Component/system identification.
— Materials of construction, fluid type, operational conditions, design limits.
— Equipment/segment volumes, economic data related to lost/deferred production.
— Inspection and operating history.
— Degradation mechanisms and failure mode, damage rate, uncertainty and basis.
— Safety risk, economic risk and risk categories.
— Risk in relation to the Risk Acceptance Limit.
— Time to reach risk limits.
— Key indicators for risk change (temperature, process changes).
— Recommendations that the part be subject to inspection, maintenance activities or monitoring of process or other parameters.
— Recommendations for additional activities in verifying the data and assumptions used in the assessments.

5.10 Execution and Evaluation

The overall recommendations and guidelines presented in all of the above need to be further customized.

For an analysis to be effectively implemented as a well-managed inspection plan, the data needs to be transferred to an inspection management database. The amount and extent of data transferred and uploaded will depend on the capability of the database as well as the data available; many databases not only manage the detailed tag-based data, but also can carry out trending analyses, store pictures, documents, data files and videos, as well as communicating directly with the NDT equipment.

Prior to transfer of data, the following issues should be considered:

1) *Data quality:* The quality of the data to be transferred should be checked as far as possible prior to upload, as it is usually easier to correct at that stage. Data relationships (hierarchy) should be maintained as for the installation asset register, to facilitate coordination with maintenance data.

2) *Working process:* The working process for both data upload as well as maintaining the data up-to-date with inspection findings, plan updates, tag data changes, and more, should be carefully evaluated. Maintenance of data integrity is essential, as is the exclusion of errors, but other points to consider are whether complex programming is needed if data transfer is to be infrequent.

3) *Updating:* In case of updating the main asset database with revised inspection plans, consideration must be given to implementation of a formal change management process, so that changes to plans and data are properly assessed by competent personnel for their effects on installation safety and operations.

4) *Data storage:* Locations for data storage should be considered. In the life of an installation, a great deal of data and information will be generated, and the pros and cons of using the inspection management database, external databases, or simple folder structures to manage the data should be evaluated. The need for easy access to data in case of a network failure or damage to server should be included in the evaluation.

5) *Infrastructure capacity:* If the inspection management database is to be made available with all functionality offshore or at remote locations, and the data server is to be maintained at a distance, consideration as to whether the data links will be sufficient to handle the necessary traffic, in addition to normal operational traffic, must be given. It may be necessary to implement a daily update from one server to another when the network is quieter, as opposed to live data in both locations.

APPENDIX A
DEGRADATION MECHANISMS & POF ASSESSMENT

A.1 Introduction

The purpose of this appendix is to guide the RBI analyst to:

— Identify which degradation mechanisms can be expected where.
— Determine damage rates and/or probability of failure for some specific materials exposed to specified service conditions.
— Present a number of simplified models for internal and external degradation.

It is emphasised that these degradation models are not exhaustive but are recommended to secure a consistent and documented methodology when better data is not available.

A.2 Degradation Mechanisms

The degradation of a component can take place externally and internally. The rate at which the degradation takes place at the two surfaces depends upon the combination of the following parameters:

1) Material of construction
2) Contents of the part (product services) (for internal degradation)
3) Environment surrounding the part (for external degradation)
4) Protective measures
5) Operating conditions.

Internal and external degradation mechanisms should be defined for each part by reference to the guidance and tables given in Sections A.6 - A.13. Assumptions used in these sections must be checked and confirmed to be applicable for the circumstances related to the individual part. If the assumptions are not valid, then specialist assistance should be sought to evaluate the specific circumstances.

The applicable degradation mechanisms should be listed for each part together with the reasons for selection.

Table A-1 gives the types of materials that have been discussed in this document.

Table A-1 Definition of materials

Material Type	*Description*	*Includes*
CS	Carbon Steel	Carbon and carbon-manganese steels, low alloy steels with SMYS less than 420 MPa.
SS	Stainless Steel	Austenitic stainless steels types UNS S304xx, UNS S316xx, UNS S321xx or similar. 22Cr duplex UNS S31803 and 25Cr super-duplex UNS S32550, UNS S32750 stainless steels or similar. Super austenitic stainless steel type 6Mo, UNS S31254.
Ti	Titanium	Wrought titanium alloys.
CuNi	Copper Nickel Alloys	90/10 Cu-Ni or similar.
FRP	Fibre Reinforced Polymer	Fibre reinforced polymer materials with polyester or epoxy matrix and glass or carbon fibre reinforcement.
Ni	Nickel-based alloys	Nickel-based alloys.
Other	Material other than the above	All other materials not described above.

A.3 Understanding PoF

This recommended practice is primarily intended to be used for the planning of in-service inspection for offshore topsides static mechanical pressure systems when considering failures by loss of containment of the pressure envelope. Such failures occur when the effect of the applied load (L) is greater than the resistance (R) of the component or material ($L > R$). The resistance R is primarily related to the materials, the design, and the in-service condition of the structure. The load L can be any type of load: functional, environmental or accidental. The reasons why ($L > R$) occurs are many, ranging from, e.g. poor design specification, design errors, and material defects, through to, e.g. fabrication errors, degradation in operation, and other unknown events.

The total probability of failure (PoF_{Total}) is the sum of the probabilities of all events that can cause a failure. It can basically be summarized as follows:

$$PoF_{Total} = PoF_{Technical} + PoF_{Accidental} + PoF_{Gross\text{-}error} + PoF_{Unknown}$$

Where:

$PoF_{Technical}$ — Natural uncertainties in design loads and load bearing capacities. $PoF_{Technical}$ is due to fundamental, natural random variability and normal man-made uncertainties.

$PoF_{Accidental}$ — Accidental events. In addition to the functional and environmental loads, there will be "accidental" events that can affect the components, e.g. dropped objects. These accidental load events can be predicted in a probabilistic form based on historical data.

$PoF_{Gross\text{-}error}$ — Gross errors during design, fabrication, installation, and operation. Gross errors are understood to be human mistakes. Management systems addressing, e.g. training, documentation, communication, project specifications and procedures, quality surveillance etc. are all put in place to avoid human error. Gross errors occur where these systems are inadequate or are not functioning. It is difficult to predict the probability of a gross error in a project. However, history shows that gross errors are not so rare. Developing, applying and following up the management system in addition to third party checks can help avoiding gross error leading to failure.

$PoF_{Unknown}$ — Unknown and/or highly unexpected phenomena. Truly unimaginable events are very rare, hard to predict and should therefore be a low contribution to failure. There is little value, therefore, in attempting to estimate these probabilities. It is worth noting that even though incredible events have low probability, they can have very high consequences, thus increasing the "risk". However, interested parties are, in general, more likely to accept consequences of truly incredible events when they have occurred.

A.3.1 Quantitative Assessment Methods

When estimating the probability of failure in a quantitative manner for the purpose of planning inspection, it is $PoF_{Technical}$ that is normally addressed. Though it is unusual, $PoF_{Accidental}$ can also be addressed. $PoF_{Gross\text{-}error}$ and $PoF_{Unknown}$ are not addressed in quantitative evaluations. Using full probabilistic models to estimate the PoF can become complex and time-consuming in the context of topside risk-based inspection. Simplified models are presented in this appendix.

A.3.2 Qualitative Assessment Methods

When estimating the probability of failure in a qualitative manner for the purpose of planning inspection, one can assume that all elements are represented in the evaluation, given that experienced and competent personnel are involved.

A.4 Hole Size Template

This recommended practice uses a set of pre-defined hole sizes that are related to those given for the degradation mechanisms. The expected percentage of holes falling within each category can be estimated or judged for each mechanism. Table A-2 shows the recommended hole sizes that are referenced in both the consequence of failure and the degradation mechanisms assessments. Appendix C gives guidance on how to adjust and utilize this type of information when assessing the consequence of failure.

Table A-2 Hole size category and the corresponding hole diameters

Small Holes	hole diameter ≤ 5 mm
Medium Holes	5 mm < hole diameter < 25 mm
Large Holes	25 mm ≤ hole diameter
Rupture (full release)	component diameter < hole diameter

A.5 Degradation Modelling and Probability of Failure (PoF) Evaluation

The purpose of the degradation modelling and probability of failure evaluation is to assess:

- current probability of failure for each tag,
- evaluate the development of damage hence PoF, with respect to time, and
- expected damage that may be incurred by a component.

The expected damage rate models can be classified into three types:

(a) Insignificant model (Section A.5.1)
(b) Unknown model (Section A.5.2)
(c) Rate model (Section A.5.3)
(d) Susceptibility model (Section A.5.4)

The behaviour of these models is shown schematically in Figure A-1.

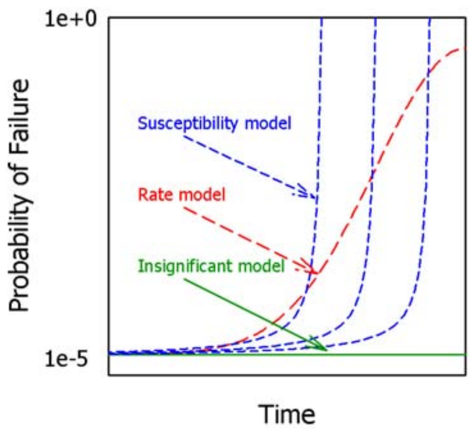

Figure A-1
Schematic curve of degradation modelling

A.5.1 Insignificant Model

For the component degrading according to the *Insignificant Model*, no significant degradation is expected. The model allocates a fixed probability of failure value (PoF = 10^{-5} per year), regardless of time, allowing a risk value to be calculated. Inspection of the components described by this model is not necessary except for checking that the premises have remained valid.

Hole sizes for analysis of consequences are given in Table A-3 and are considered generally applicable in offshore systems.

Table A-3 Hole size distribution for "Insignificant" systems

	% Distribution		
Equivalent Hole Diameter	*Carbon Steels*	*Stainless Steel and Nickel-based Alloys*	*Titanium-based Alloys*
Small Hole	0	0	100
Medium Hole	0	100	0
Large Hole	100	0	0
Rupture	0	0	0

A.5.2 Unknown Model

Where the product is an unknown substance, or the combination of materials and product has no defined model, then initially a probability of failure of 1 should be assigned and the need for further investigation driven by the consequence of failure – where a high consequence of failure will give a high risk, indicating that it will be beneficial in spending further time in investigation of product and materials.

The hole sizes required to calculate consequences are given in Table A-4.

Table A-4 Hole size distribution for "Unknown" systems

Equivalent Hole Diameter	*% Distribution*
Small Hole	0
Medium Hole	0
Large Hole	0
Rupture	100

A.5.3 Rate Model

The *Rate Model* is normally applicable when the damage results in a local or general wall thinning of the component. It assumes that with time the extent of damage increases, resulting in a decrease of wall thickness. This in turn manifests as an increase in the probability of failure with time.

The rate of degradation, hence, the rate of decrease in the wall thickness, is dependent upon a number of factors. These include:

— material properties
— wall thickness
— fluid properties
— operating conditions.

All these factors vary and a full probabilistic assessment should consider every factor as a stochastic variable. In practice, however, the uncertainties associated with the degradation drivers (e.g. pressure, flow rate) tend to outweigh the uncertainties of the other variables. This allows some simplification to be used without significant loss of precision.

A simplified rate model can be described by distribution type, mean and standard deviation. This appendix suggests these parameters for different degradation scenarios.

The calculation of probability of failure can be carried out using Monte Carlo simulation or the First Order Reliability Methods (FORM) using distributions for all the most important factors. These calculations are best carried out using computer techniques and are likely to require a specialist in mathematical and statistical techniques to develop the algorithms. A number of suitable software tools are also available that include these methods as part of RBI calculations.

Since the degradation increases with time, the development of degradation can be measured by inspection, thus the inspection results can be used to adjust the rate model to suit the actual situation.

A.5.4 Susceptibility Model

The damage of components described by the *Susceptibility Model* is triggered by an external event after a dormant period of an unknown duration. Once triggered the damage occurs very quickly. This model gives a fixed value for probability of failure depending on factors relating to operating conditions. For a given set of conditions that are constant over time, the probability of failure also remains constant over time.

Since the mechanism is such that the damage can be triggered at any time and thereafter proceed rapidly, the onset and development of the damage are difficult to follow by inspection. However, it is beneficial to monitor key process parameters, such as excursions or a change of conditions that can trigger degradation.

A.5.5 Steps in Modelling Degradation

The damage models for the degradation mechanisms given in this appendix follow the process given below. The same basic steps should be used if alternative models or other degradation mechanisms are applied in the RBI analysis:

1) Assess which mechanism is expected in a given case.
2) Determine damage rate and/or failure probability:

   — Time dependent mechanisms require distribution type with a mean value, standard deviation or equivalent. PoF is derived from the rate and structural reliability calculations.
   — Susceptibility mechanisms do not have a rate, but PoF is derived based on engineering judgement directly from key parameters.

3) Determine damage morphology: three types are defined:

   — Local: localised damage that does not interfere with the load bearing capacity of the equipment wall. Probability of failure refers to a small leak at wall penetration.
   — Uniform: damage of such a large area that affects the load bearing capacity of the equipment wall. Probability of failure refers to the state when the wall ligament cannot accommodate the loading as calculated using structural reliability analyses. Typically it results in a large release.
   — Cracking: a crack that penetrates the wall. A virtual crack is assigned a single size and checked for “leak before break”, giving leak or rupture failure respectively.

4) Define hole sizes expected on failure:

   — Expected hole sizes at failure for each degradation mechanism are stipulated in accordance with a standard hole size distribution template.

A.6 External Damage

External damage is related to the external environment and condition of the surface protection. The damage rate can either be of the type “insignificant”, “unknown”, “rate” or “susceptibility”. It is evaluated independently of any internal degradation and damage. It applies to all metallic materials with or without coatings and/or insulation.

A.6.1 External Corrosion - Uninsulated

The external degradation models allow calculation of probability of failure for different materials on the assumption that they are exposed to the marine atmosphere, or are expected to be wetted by seawater, e.g. deluge system. Seawater may also collect on pipe supports and clamps and similar locations, promoting corrosion damage on uninsulated piping.

A.6.2 External Corrosion - Coated

The corrosion rate may be reduced by applying coating on the surface. The effectiveness of the coating can be assumed to be near-perfect during the initial period, and thereafter it falls. The deterioration pattern depends upon the coating system and maintenance. The details regarding the coating specifications and coating condition should be obtained from the client. In case the details about the coating are not available, then treat as if the coating is not present.

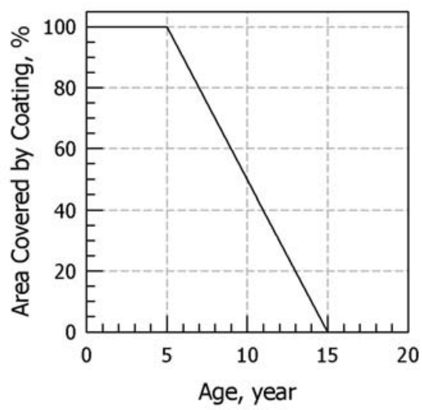

Figure A-2
Coating degradation as a function of time

In general, coatings applied in accordance with NORSOK standards or similar have a full protection period of five years and no protection after fifteen years. This can be taken as a default coating effectiveness model (Figure A-2). The deterioration pattern can be changed to account for different coating systems and maintenance. The degradation rate of the coated structure is then equal to (100 – *Effectiveness*)/100.

A.6.3 External Corrosion - Insulated

Surfaces under insulation are not readily available for visual inspection, and if water penetrates the weather protection, high salt can accumulate on the metal surface leading to possible severe local corrosion.

In order to assess external damage under insulation or Corrosion Under Insulation (CUI) the details about the insulation and the conditions of assessment must be collected and then the assessment carried out. As a general guideline:

1) It is conservative to assume that all fibre-based insulation is water-retaining, and damaged sufficiently to allow water penetration, irrespective of what outer protection is specified.
2) Personnel protection insulation may consist of a wire mesh used to prevent physical contact with hot pipes; this will not retain water, and the above assumption will be unnecessarily conservative.
3) Passive fire protective coating would not normally be expected to retain water if in good condition; if this is cracked and otherwise poorly maintained, water retention is possible.

Likely areas for corrosion under CUI may be found by external visual inspection of the insulation where water can penetrate (such as faulty caulking or damaged cladding). CUI may be detected by visual examination of the pipe surface after removal of the insulation. Radiographic examination can be used to view the pipe wall profile through the insulation, thereby obviating its removal and reinstatement. Similarly, radiographic and thermal imaging methods may be useful for identifying water in the insulation. A coating under the insulation will reduce probability of attack, but the deterioration of the coating over time must be considered. The quality and condition of coating and insulation work has to be assessed from case to case. Strategise for corrosion control under insulation will depend upon the condition and maintenance of coating and insulation. Further information can be found in *Corrosion Under Insulation (CUI) Guidelines (EFC 55)* published by the European Federation of Corrosion [EFC, 2008].

A.6.4 Steps in Modelling External Degradation

The calculation of external degradation is done by the following steps:

1) Define the material type as given in Table A-1.
2) Determine the operating conditions applicable to the part under consideration. Take into account temperature and presence and condition of coating.
3) Go to relevant sections to calculate the degradation rate or probability of failure as applicable.

A.7 Internal Damage

This section discusses some of the most relevant services, materials and degradation mechanisms for internal damage. The discussion is based on general knowledge gathered from operating companies and open literature. All combinations of materials and services have not been covered, and expert evaluations may be needed where these are missing.

Internal damage mechanisms are based on combinations of material of construction, operating conditions and fluids flowing in the pipe. As a guideline, the Product Service Codes used on offshore topside systems, can give an indication of the type of fluid that can be expected to flow in the pipe.

A.7.1 Product Service Code Definition

The objective of the Product Service Codes is to aid in determining the possible degradation mechanisms for the component under consideration. This assessment is based on general experience and fundamental knowledge of materials and service. The outcome of the assessment is a conservative listing of components with their possible degradation mechanisms. Table A-5 lists the two character Product Service Codes and the contents that are assumed as the basis for internal degradation models.

Often Product Service Codes different from those listed in Table A-5 will be encountered while assessing installations. For such conditions it is important that installation-specific codes be checked and matched to the descriptions given in the table. Incorrect evaluations with the degradation mechanisms may occur if the fluids do not conform exactly to the descriptions given in the table. Specialist advice should be sought if there are discrepancies.

Although the product service codes are used to determine the expected internal degradation mechanism, this is a simplification and the limitations must be recognised, and accounted for in each analysis:

- The product service code does not always provide sufficient differentiation with respect to fluid corrosiveness. It is necessary to review the system and split it into more detailed areas, e.g. to identify where hydrocarbon gas is dry and wet.
- The product service code may not reflect some operational practices, e.g. closed drains may be used as a bypass system.
- The product service code may not reflect content, e.g. closed drains may be used as a bypass system.
- Some of the product service codes are so unspecific or variable that the contents must be assessed by suitably qualified personnel.
- The materials listed are intended to give general and conservative results. The calculations can be improved if more precise materials’ specifications are used.
- The models have limits on their applicability, and it should be verified that the model is applicable to the situation at hand; in all cases, there is an upper temperature limit of 150°C.
- Where the conditions given in this appendix do not match with those found in the plant, specialist advice must be sought.

Table A-5 Product Service Code with descriptions and degradation mechanism group		
Product Service Code	*Description*	*Degradation Group*
AI	Air Instrument *Compressed air system for pneumatic controllers and valve actuators and purging of electrical motors and panels. Comprises dry, inert gas.*	Insignificant
AP	Air Plant *Compressed air system for air hoists/winches, air motors, sand blasting, spray painting, air tools and motor purging. Typically not dried, so parts may contain water vapour and condensation. Condensed water can be considered as being fresh.*	Waters
BC	Bulk Cement *Cement powder, generally in dry form.*	Chemicals
BL	Cement Liquid Additive *May be proprietary liquids. Plasticisers, accelerators and retarders added as liquid to liquid cement to adjust the flow and curing characteristics.*	Chemicals
CA	Chemical, Methanol *Used to prevent and dissolve hydrates in water containing hydrocarbon gas systems. Should contain less than 2% water by volume. May be used as water scavenger.*	Insignificant
CB	Chemical, Biocide *May be proprietary fluid biocide such as glutaraldehyde, or chlorine (from electrolysis of seawater or from addition of sodium hypochlorite, etc.).*	Chemicals
CC	Chemical, Catalyst *May be proprietary fluid catalyst for chemical reaction control.*	Chemicals
CD	Chemical, Scale Inhibitor *May be proprietary scale inhibitor used to prevent scale problems arising from $BaSO_4$ (typically downhole) and $CaCO_3$ (typically surface and heater problems).*	Chemicals
CE	Chemical, Demulsifier or Defoamant *May be proprietary fluid defoamant / emulsion breaker for water content control in oil by aiding separation of oil and water.*	Chemicals
CF	Chemical, Surface Active Fluid *May be proprietary fluid surfactant with dual hydrocarbon and polar character and dissolves partly in hydrocarbon and partly in aqueous phases.*	Chemicals
CG	Chemical, Glycol *100% glycol, which is not considered corrosive.*	Insignificant
CH	Chemical, AFFF *Fire fighting foam additive to firewater.*	Insignificant
CJ	pH Controller *May be proprietary chemical for buffers typically to raise the pH.*	Chemicals
CK	Corrosion Inhibitor *May be proprietary fluid for injection as corrosion protection. Usually not corrosive in undiluted concentration.*	Insignificant
CM	Cement High/Low Pressure *Cement mixed with a carrier, usually seawater, and used downhole. Likely to be erosive.*	Chemicals
CN	Chemical, Mud Additive *Typically mud acids (e.g. HCl, HF).*	Chemicals
CO	Chemical, Oxygen Scavenger *Oxygen scavenger. (Typically Sodium bisulphite Na_2S). Corrosiveness depends on type, and possibly concentration and temperature. Moderate to low concentrations can be tolerated in a variety of materials, but high concentrations may be corrosive.*	Chemicals
CP	Chemical, Polyelectrolyte/Flocculent *May be proprietary fluid flocculent for oil content control in produced water.*	Chemicals
CS	Chemical, Sodium Hypochlorite Solution *Concentrated NaClO for supply to each consumer. Corrosiveness depends on concentration and temperature.*	Chemicals
CV	Chemical, Wax Inhibitor *May be proprietary wax inhibitor for use in produced liquids to hinder formation of waxes as temperatures are reduced.*	Chemicals
CW	Chemical, Glycol/Water (Rich Glycol to Regenerator) *Regeneration system to remove water from Glycol/Water. Part of the gas drying system. The system is in contact with hydrocarbons. This, and the rich part of the regenerator, is likely to be the most corrosive area of the system. System fluids are regularly checked for pH due to Glycol breakdown.Note: lean Glycol corrosiveness is dependent on water content and composition.*	Chemicals

Table A-5 Product Service Code with descriptions and degradation mechanism group (Continued)		
Product Service Code	*Description*	*Degradation Group*
DC	Closed Drain System *Hydrocarbon liquids in drains from platform equipment and piping, collected in a closed vessel. Intermittent use or low flow rates leading to stagnation. May have fuel gas blanket at low pressure. Liquids comprise hydrocarbon oil, gas, water, in proportions according to the equipment drained. There is potential for microbial action.*	Hydrocarbons
DO	Drain, Open *Drain from helideck, roof drain and drain from test lines, etc. Mostly seawater and rainwater, but some oil likely. Under atmospheric pressure.*	Waters
DS	Drain, Sewer/Sanitary *Closed system. Drain from living quarters containing domestic sewage.*	Waters
DW	Drain Water/Storm *Open system. Accumulated water from sea spray and rain led to floor gullies.*	Waters
FC	Completion Fluid High/Low Pressure	Chemicals
FJ	Fuel, Jet *Clean, water-free aviation fuel (kerosene) for helicopters.*	Insignificant
GA	Gas, Firefighting/CO_2 *Dry, typically bottled, CO_2 used as extinguishing gas.*	Insignificant
GF	Gas, Fuel *Process gas used to fuel compressors and generators. Dried hydrocarbon gas with CO_2 and H_2S in the same quantities as the process system.*	Insignificant
GI	Gas, Inert *Inert gas, such as nitrogen or dry CO_2. Note: some installations use exhaust gas for inerting storage tanks with this product service code, and these should be considered as cold exhaust gas.*	Insignificant
GW	Gas, Waste/Flue *Products of burning hydrocarbon gas or diesel fuel. Acidic combustion products may condense in exhaust piping causing high corrosion rates.*	Vents
MB	Mud, Bulk/Solid *Storage of mud components prior to mixing.*	Chemicals
MH	Mud, High Pressure *High pressure mud pumping system for deliverance of drilling and completion fluids in normal use. May contain well intervention fluids, completion and packer brine fluids, mud acids (HCl, HF), well stimulation fluids, scale inhibitors, methanol, diesel, varying densities of byrites or other solids.*	Chemicals
MK	Mud, Kill *Mud pumped into the well for well control purposes. May contain heavy densities of byrites or other solids.*	Chemicals
ML	Mud, Low Pressure *As MH.*	Chemicals
OF	Oil, Fuel (Diesel oil) *Diesel fuel for use in cranes, generators and well pressure equalisation. Usually dry, but may contain water and organic matter that settles in low/stagnant points.*	Insignificant
OH	Oil, Hydraulic *Clean, dry, filtered hydraulic oil for actuators.*	Insignificant
OL	Oil, Lubricating *Clean, dry, filtered oil for lubrication purposes.*	Insignificant
OS	Oil, Seal*Clean, dry, filtered seal oil for gas compressors. May contain amounts of dissolved process gas.*	Insignificant
PB	Process Blow-Down *Wet hydrocarbon gas. Parts of system are vents and flare. Will contain CO_2 and H_2S in the same proportions as the systems blown down. Normally purged with fuel gas at low pressure.*	Hydrocarbons
PL	Process Hydrocarbons, Liquid *Untreated liquid hydrocarbons (post inlet separator).Contains some gas but mostly hydrocarbon liquid with some water, dissolved CO_2 and H_2S, potential for sand. May also contain small amounts of CO_2 corrosion inhibitor, scale inhibitor, emulsion breaker and other chemicals. Water contains high levels of dissolved salts from the reservoir. If water injection is part of the process, may contain bacteria that can colonise stagnant areas.*	Hydrocarbons
PS	Process Hydrocarbons, Vapour Wet *Wet untreated gas where water vapour is expected to condense into liquid. Contains CO_2 and H_2S in the same proportions as the reservoir.*	Hydrocarbons
PT	Process Hydrocarbons, Two Phase *Untreated two phase flow upstream of inlet separator. Contains oil, gas, water, sand, also CO_2 and H_2S in the same proportions as the reservoir. May also have inhibitor and stabilisation chemicals injected close to wellhead. If water injection is part of the process, may contain bacteria that can colonise stagnant areas.*	Hydrocarbons

Table A-5 Product Service Code with descriptions and degradation mechanism group (Continued)		
Product Service Code	*Description*	*Degradation Group*
PV	Process Hydrocarbons, Vapour *Dry hydrocarbon gas where water is not expected to condense as liquid. (Post separator.) Contains CO_2 and H_2S in the same proportions as the reservoir.*	Hydrocarbons
PW	Produced Water System *Water from the production separators. It contains water with dissolved CO_2 and H_2S in the same proportions as the reservoir, and some oil. Sand may be carried over from the separator.*	Hydrocarbons
SP	Steam, Process	Not Included*
SU	Steam, Utility/Plant	Not Included*
VA	Vent, Atmospheric	Vents
VF	Vent, Flare	Vents
WA	Water, Sea Anti-liquefaction	Waters
WB	Water, Sea Ballast/Grout *Oxygen rich seawater that may be treated with biocide/chlorination.*	Waters
WC	Water, Fresh/Glycol Cooling Medium *A closed system where direct seawater cooling is not applicable. Fresh or desalinated water treated with TEG, regularly checked for low pH arising from breakdown of the TEG.*	Waters
WD	Water, Fresh Potable *Oxygen rich, chlorinated fresh water often with small amounts of salts added for palatability. Max Cl^- ions concentration 200 ppm.*	Waters
WF	Water, Sea Firefighting *Closed seawater system treated with biocides/chlorination.*	Waters
WG	Water, Grouting Systems *Used for make up of cementitious grout during installation or drilling operations. May be either raw seawater or desalinated seawater.*	Waters
WH	Water, Fresh/Glycol (TEG) Heating Medium *Heating medium providing required heat load to process and utility equipment.* *Fresh or desalinated water mixed with TEG. May also contain corrosion inhibitor. Regularly checked for pH due to breakdown of the TEG.*	Waters
WI	Water, Injection *Injected water used for enhanced reservoir recovery. May be treated produced water, treated seawater, or combination.*	Water Injection
WJ	Water, Jet *Jet water supply for removing of sand from separators, cleaning of tanks etc. May be supplied from produced water, fresh water, disinfected, or treated seawater. May also require addition of anti-scale chemicals.*	Waters
WP	Water, Fresh, Raw *Desalinated, oxygen rich, untreated water.*	Waters
WQ	Water, Fresh, Hot (closed circuit) *Fresh or desalinated, oxygen rich, untreated hot water for living quarter and equivalent.*	Waters
WS	Water, Sea *Oxygen rich, seawater for distribution to the various platform users. May be treated with chlorination to prevent biological growth within the system.*	Waters
* Steam (SP & SU) are expected to have a normal operating temperature > 150°C.		

Table A-6 Water categories - definition and description	
Material Type	Description
Raw Seawater	*Seawater:* Untreated, normal oxygen, bacteria, marine flora etc.
Seawater + Biocide/ Chlorination	*Seawater:* Treated with UV/filtered or bactericide, chlorinated.
Seawater Low Oxygen	*Seawater:* Deoxygenated (max. 50 ppb O_2). No other treatment.
Seawater Low Oxygen + Biocide	*Seawater:* Deoxygenated (max. 50 ppb O_2), treated with UV/filtered or bactericide. No chlorination.
Seawater Low Oxygen + Chlorination	*Seawater:* Deoxygenated (max. 50 ppb O_2) and chlorinated.
Seawater Low Oxygen + Biocide + Chlorination	*Seawater:* Deoxygenated (max. 50 ppb O_2), treated with UV/filtered or bactericide, chlorinated.
Fresh Water	*Desalinated Water:* Typically prepared by condensation of seawater. Basis for plant water for steam generation etc., low salt content, normal oxygen.
Closed Loop	*Closed loop systems:* Desalinated systems that have intrinsically “low” oxygen content.
Exposed Drains	*Seawater:* Open systems that collect water from drains, sluices, deluge, etc., and are assumed to contain untreated (raw) seawater.
Sanitary Drains	*Fresh water:* Drains from sanitary systems. Fresh water with high bacteria and organic matter content.

A.7.2 Internal Degradation Mechanism - Sand Erosion

Degradation due to sand erosion gives general wall thinning where the product flow impinges on the pipe or vessel wall, such as at changes in flow direction, or areas where obstructions cause eddying, such as at valves or orifice plates. The rate of wall loss by erosion increases with the quantity of sand in the product and the product flow rate. Detection and estimation of sand rate can be by acoustic monitoring, the examination of coupons, or the frequency of separator jetting. Inspection for the presence of erosion can be by internal visual, external ultrasonic or radiographic examination of the internal surface where allowed by access and geometry.

A.7.3 Internal Degradation Mechanism - Water Systems

Water systems use “water” of varying corrosiveness, ranging from untreated seawater to potable water. The product codes for the water containing systems are not sufficient to define the water type with respect to corrosiveness, and do not account for changes that can occur during processing; for example, in a system “raw seawater” after treatment can become “fresh water”.

A number of water categories that are commonly encountered in offshore installations have been defined, as given in Table A-6. It is necessary to determine the best match between a water category and the Product Service Code used in each water system, or part of a system. This can be established during screening discussions and/or with reference to process drawings.

Appropriate corrosion mechanisms have been assigned for each of the water categories. These include:

- Uniform corrosion is assumed in carbon steels and the PoF is derived from wall thinning rate.
- Local corrosion such as pitting and crevice corrosion that is expected in stainless steels in oxygenated waters. These degradation mechanisms return a PoF based on susceptibility and constant over time for given operational parameters.
- Microbial corrosion (also called microbiologically-influenced corrosion or MIC) in waters takes place where organic life can be sustained and no effective biocides are used.

Note that:

- Produced water is included with hydrocarbon systems.
- Water Injection systems use various types of treatment, and must be considered on a case to case basis.

A.7.4 Internal Degradation Mechanism - Microbiologically-Influenced Corrosion (MIC)

Bacterial growth in the presence of water and nutrients gives rise to MIC, causing pits on internal surfaces. It is associated with the water phase, and so is likely to be located where water can drop into dead legs or other areas of stagnant flow. Thus, in piping, the MIC generally takes place in side-lines, such as small bore appurtenances for instrumentation, and not the main pipe itself where flow rate is generally high enough to preclude MIC. Under the conditions of low flow rates and internal deposition, MIC has also been seen in main pipes. Since the cause of MIC is biological, the absence of water, absence of nutrients or presence of extreme temperatures will prevent or slow its development.

MIC pits may be widely spaced within a system so detection of damage is difficult, unless high coverage inspection is used. Inspection of these pits will require extensive ultrasonic (less unreliable), radiographic (reliable) or internal visual inspection (reliable). It is therefore generally advisable to start by monitoring for the presence of microbes (bacteria sampling). This can be by visual investigation of filters and stagnant bottom sludges. More detailed analysis should also address the location of biocide injection points and effectiveness of the biocide. The detection of MIC in one part of a system suggests strongly that it will be present in the remainder of the similar systems on the installation.

A.7.5 Internal Degradation Mechanism - Hydrocarbon Systems

The multiphase hydrocarbon-water-gas systems, like produced water and closed drains, must be evaluated with respect to the presence of the hydrocarbons along with corrosion and cracking respectively due to the dissolution of CO_2 and H_2S, in water. In some circumstances microbial corrosion can also occur. Additionally, any sand that is entrained in the system can cause sand erosion where the flow impinges on the pipe or equipment surface.

The presence and composition of water varies through the processing train hence, the Product Service Codes have limited value in guiding expected degradation. It is thus necessary to study the process flow to identify, split and group equipment with similar environmental and operational conditions. The following points should also be considered:

- Chemical treatment (inhibition) is commonly used to limit CO_2 corrosion in carbon steel and injection points and inhibitor performance must be evaluated.
- Hydrocarbon production processes are expected to change over time and these must be considered when planning inspection, e.g. lower pressure, water breakthrough.
- Hydrocarbon systems usually employ various types of corrosion monitoring and have traditionally received high inspection focus. Service data (condition, integrity and process data) may be available for installations that have been in service, and these data should be evaluated and used together with the models given here.

Expected damage can be calculated for various degradation mechanisms using the following factors for guidance:

- Assess the presence of water and its composition and pH.
- Assess the equivalent partial pressure of CO_2 and H_2S gases in a water phase.
- Assess possible presence and effects of MIC.
- Determine PoF due to HPIC/SOHIC due to presence of H_2S.
- Determine PoF due to SSC.
- Determine PoF due to CO_2-corrosion.
- Assess effects of chemical treatments, internal organic coatings and cathodic protection.
- Determine PoF due to sand erosion.

A.7.6 Internal Degradation Mechanism - Chemicals

Chemicals can be split into three groups:

- *Proprietary chemicals* - These include, but are not limited to, corrosion inhibitors, flocculants, bactericides.
- *Drilling chemicals* - These have limited interest on a production installation.
- *Identifiable chemicals* - These are common chemicals, but corrosiveness is dependent on concentration and temperature.

The first two groups may have chemicals given by trade names only. In many cases they may be non-corrosive and innocuous in service conditions; however, in other cases, particularly at high concentrations, they can be highly corrosive and/or toxic.

The third group includes chemicals, for which general corrosion data is more readily available, although the possible variation in type and concentration implies that corrosiveness must be evaluated on a case by case basis. These are typically systems that should be discussed during screening; the consequence is expected to be low in most cases and many components can be expected to be screened out with very little further effort required.

It is common that chemical systems can be assessed as either "Insignificant" or "Unknown" systems as discussed earlier.

A.7.7 Internal Degradation Mechanism - Vent Systems

The vent system collects vapour phase from various parts of the process. Each part of the vent system must be evaluated with respect to what is being vented. Generally, the vent lines will be subject to the same degradation mechanisms as vapour phase in the equipment being vented.

Vent system equipment, such as knock-out drums may collect vapours from several areas and should be considered with respect to the composition of any liquid phases that they may collect.

A.7.8 Internal Degradation Mechanism - Water Injection Systems

Water injection systems usually use large volumes of treated water. This may be based on seawater, produced water, or a combination of these. Treatment typically includes de-oxygenation or de-aeration, chlorination or similar biocide, pH buffering, anti-scaling. Significant amounts of CO_2 may be dissolved in the water. High injection rates imply that flow-related damage can arise. A variety of materials are deployed in water injection systems, and correct treatment (relative to the materials) is essential. It is recommended that water injection systems be addressed on a case for case basis; however, in many cases the water injection system can be evaluated as equivalent to a water system and/or produced water.

A.7.9 Steps in Modelling Internal Degradation Mechanism

The user is advised to ensure that the conditions on the asset in question match those listed in the section before using the models; deviations should be referred to a specialist for advice.

The calculation of probability of failure due to internal degradation follows the process below:

1) Define the material type, as given in Table A-1.
2) Define the appropriate Product Service Code and identify the potentially corrosive contents. Refer to Table A-5.
3) Determine the service conditions applicable to the part in question, comprising temperatures, pressures, amounts of corrosive species.
4) Go to the relevant sections (Sections A.8-A.12) and calculate the degradation rate or probability of failure as applicable.

A.8 Carbon Steel

A.8.1 External Corrosion of Carbon Steel Piping

Carbon steels suffer marked external corrosion, but to mitigate the problem they are usually protected by a coating.

A.8.1.1 External Corrosion of Uninsulated Carbon Steel Piping

External corrosion of uninsulated carbon steel piping is due to exposure to marine atmosphere. Corrosion rate increases with temperature and with coating breakdown. The external corrosion rate of uninsulated and uncoated carbon steel piping is a function of temperature and is modelled as a normal distribution characterised by the mean and standard deviation (Table A-7).

The external corrosion of uninsulated carbon steel piping is assumed to result in "uniform wall thinning" occurring in areas or "patches". This can lead to bursts at the thinnest part of the patch when the local stress exceeds the material's strength. The leak holes generated are normally small and usually occur in connection with a patch. The hole size distribution in the piping containing leak holes is given in Table A-8.

Inspection for atmospheric corrosion can be by external visual inspection, concentrating on areas where weathering is most likely or where water can collect, such as under clamps.

Table A-7 External corrosion rates of uninsulated carbon steel piping

Temperature (T) Range	*Mean (mm/year)*	*Standard Deviation (mm/year)*	*Notes*
$T < -5°C$	*Not Applicable*	*Not Applicable*	$PoF = 10^{-5}$
$-5°C < T < 20°C$	0.1	0.05	-
$20°C < T < 100°C$	$0.3547 \times \ln(T)$-0.9334	$0.3929 \times \ln(T)$ -1.0093	-
$100°C < T$	-	-	Surface drying occurs and will affect the corrosion rate. Refer to a specialist.

Table A-8 Hole size distribution due to external corrosion of uninsulated carbon steel piping

Equivalent Hole Diameter	*% Distribution*
Small Hole	90
Medium Hole	9
Large Hole	1
Rupture	0

Table A-9 External corrosion rates of insulated carbon steel piping

Temperature (T) Range	*Mean (mm/year)*	*Standard Deviation (mm/year)*	*Notes*
$T < -5°C$	-	-	$PoF = 10^{-5}$
$-5°C < T < 20°C$	As 20°C	0.286	May overestimate rate, but failures found at low temperatures.
$20°C < T < 100°C$	$0.0067 \times T + 0.3000$	0.286	
$100°C < T$			Refer to a specialist.

Table A-10 Hole size distribution due to external corrosion of insulated carbon steel piping	
Equivalent Hole Diameter	*% Distribution*
Small Hole	80
Medium Hole	20
Large Hole	0
Rupture	0

A.8.1.2 External Corrosion of Insulated Carbon Steel Piping

The external corrosion of insulated carbon steel piping occurs when the insulation traps moisture in its porous structure and attacks the external wall of the piping. This results in the external uniform or local corrosion defects. The rate of corrosion increases with the increase in the exposure to water and increase in temperature. Above 100ºC the wet insulation will dry out, but in the process will concentrate salts. This will result in accelerated corrosion rates during the period when the temperature is rising. Subsequent cooling will also result in rapid corrosion due to re-hydration of the deposited salts.

The external corrosion of insulated carbon steel piping is modelled as a normal distribution with mean and standard deviations, as in Table A-9, on the assumption that salt water (from deluge) is wetting the insulation. If the insulation is shown not to be wet, the model does not apply. The rates can be reduced by increasing the coating efficiency.

CUI is expected to occur in patches where conducive conditions occur. The damage is not expected to interfere significantly with wall stresses and leak, rather than burst, is expected. Hole sizes are expected as given in Table A-10.

Table A-11 Hole size distribution in carbon steel piping internally degraded by erosion	
Equivalent Hole Diameter	*% Distribution*
Small Hole	0
Medium Hole	0
Large Hole	0
Rupture	100

A.8.2 Internal Corrosion of Carbon Steel

A.8.2.1 Internal Corrosion of Carbon Steel Piping - Erosion

The rate of erosion can be described by normal distribution. The mean of the distribution can be calculated according to the model given in the DNV-RP-O501 [DNV 2005b] and the coefficient of variance is taken as 0.20.

The damage morphology is “uniform” type and the hole size distribution is given in Table A-11.

A.8.2.2 Internal Corrosion of Carbon Steel Piping - Water

The internal corrosion of carbon steel piping due to water covers corrosion due to different categories of water, as defined in the Table A-6. Corrosion rates increase with the increase in flow rate, oxygen concentration and temperature. The rates are also applicable to carbon steel where an organic coating is damaged. The use of TEG at concentrations of 30% in closed systems is effective in reducing corrosion to very low rates. Inspection can be by external radiography or ultrasonics to measure wall loss.

The rate of internal corrosion of carbon steel piping due to water can be described by normal distribution defined by mean and standard deviation. Table A-12 gives the description of the corrosion rates by water type for given temperature and flow conditions.

The corrosion due to water results in uniform wall thinning, but this may become localised if internal scales form and break down in patches. The hole size distribution is given in Table A-13.

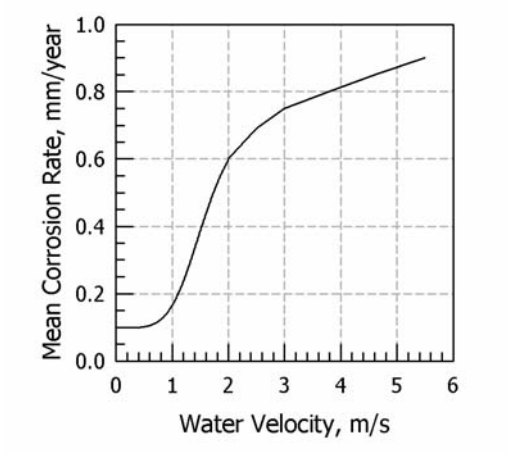

Figure A-3
Carbon steel corrosion rates’ variation with flow rate of sea water

Table A-12 Corrosion rates in carbon steel piping by different categories of water		
Material Type	*Mean (mm/year)*	*Standard Deviation (mm/year)*
Raw Seawater	Flow dependent: Rates from Figure A-3.	0.1
Seawater + Biocide/Chlorination	Flow dependent: Rates from Figure A-3.	0.1
Seawater Low Oxygen	0.01	0.01
Seawater Low Oxygen + Biocide	0.01	0.01
Seawater Low Oxygen + Chlorination	0.01	0.01
Seawater Low Oxygen + Biocide + Chlorination	0.01	0.01
Fresh Water (Cl less than 200 ppm)	0.25	0.1
Closed Loop	0.01	0.01
Exposed Drains	Flow dependent: Rates from Figure A-3.	0.1
Sanitary Drains	Treat as MIC. Rates from Figure A-4.	0.1

Table A-13 Hole size distribution in carbon steel piping internally degraded by aqueous corrosion	
Equivalent Hole Diameter	*% Distribution*
Small Hole	0
Medium Hole	0
Large Hole	100
Rupture	0

Table A-14 Notes regarding internal corrosion of carbon steel piping in water systems

Consideration	*Notes*
Galvanised Steel/Zinc	Internal galvanisation is rarely effective in long-term corrosion control, and so no credit should be given to galvanised steel: it is treated as carbon steel. Beware clogging of nozzles due to zinc corrosion products.
Cement Linings	No credit should be given for these linings: it is treated as carbon steel. Inspection should include procedures for examining the condition of the lining.
Organic Linings	Organic linings should be identified; their performance must be estimated on a case for case basis. A degradation profile may be defined and applied to the corrosion rates given in this document. A procedure for defining a degradation profile is given in external corrosion models.
Cathodic Protection	The theoretical performance of sacrificial anode systems can be checked by reference to procedures such as NORSOK and DNV-RP-B401, whilst monitoring/inspection of the anode consumption should give a good indication of their effectiveness in practice. Note that, to be effective, anodes should be placed so they lie in the water phase.
Galvanic Corrosion	Galvanic corrosion may occur with certain material combinations, typically between carbon steel and stainless steel. The extent of damage is dependent on the relative areas of the materials, and the resistivity of the media. In some cases this is advantageous, for example where pumps and valves with lower grade stainless steel housings are used in carbon steel pipework, the stainless steel will be "protected" by the carbon steel. In other cases, for example where there is a large cathodic area, high corrosion rates can be expected. Correct assignment of anode and cathode for many common material combinations is strongly affected by local conditions, thus any abrupt changes in materials should be identified and referred to a specialist for evaluation.
Welds	Corrosion of welds in carbon steel water bearing systems is variable. All or part of the weldment may be attacked. Initial inspection should target welds and parent materials. Inspection findings, if any, can be reviewed to determine where future inspections can be focused. These comments also suggest that data from on line monitoring, e.g. corrosion probes, iron counts, should be used with caution, preferably as a supplement to some inspection.

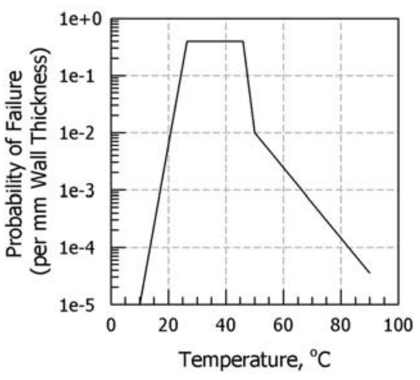

Figure A-4
PoF against temperature for microbial corrosion (MIC)

Table A-15 Hole size distribution in carbon steel piping internally degraded by MIC

Equivalent Hole Diameter	*% Distribution*
Small Hole	90
Medium Hole	10
Large Hole	0
Rupture	0

A.8.2.3 Internal Corrosion of Carbon Steel Piping - Microbiologically Induced Corrosion (MIC)

The microbial corrosion is generally not expected in other materials than carbon steels in anaerobic hydrocarbon systems. However, this should be evaluated for each system and the conclusions and assumptions should be documented.

Figure A-4 shows a suggested plot for PoF as function of temperature for the internal MIC corrosion of carbon steel pipe. For a pipe under consideration, read the PoF value from the figure and divide by wall thickness of the pipe (in mm).

The damage morphology due to microbial corrosion is "leak" and the hole size distribution is given in Table A-15.

Table A-16 Hole size distribution in carbon steel piping internally degraded by CO_2 corrosion

Equivalent Hole Diameter	*% Distribution*	
	Uniform Corrosion	*Local Corrosion*
Small Hole	0	50
Medium Hole	0	50
Large Hole	0	0
Rupture	100	0

A.8.2.4 Internal Corrosion of Carbon Steel Piping - CO_2 corrosion

CO_2 corrosion of carbon steel piping takes place in the presence of the gas-water-hydrocarbon multiphase system. It is associated with the water phase, and is therefore likely to be located where water is consistently in contact with the metal surface. Such areas are around the 6 o'clock position in piping; however, CO_2 corrosion may also be seen around the 12 o'clock position where uninhibited water vapour condenses on the metal surface. The corrosion is also likely in dead legs and other water traps, including irregularities at welds. Complete dehydration prevents CO_2 corrosion.

CO_2 corrosion rate increases with the increase in CO_2 content (expressed as mole% or volume% in the gas phase) and total pressure. It decreases with the increase in pH and effectiveness of corrosion inhibitor. For example, methanol injection can have an inhibition effect. It can either increase or decrease with temperature, depending on the temperature and the presence or absence of protective scales. Corrosion inhibitor failure can often be tolerated for short periods, but extended lack of inhibition may give rise to extensive degradation.

Coupons can be used to detect corrosion and monitor inhibitor effectiveness. While carrying out the study, consideration must be given to their location with reference to water content. Rate measurement and inspection can be done by (1) internal visual or external ultrasonic examination over areas for the uniform thinning and (2) internal visual, extensive external ultrasonic or radiographic examination of the internal surface for local wall loss. In all cases, it is essential that hot spots be identified.

Due to the CO_2 corrosion, both "local" and "uniform" damage ("uniform" refers to larger areas of damage, typically 6 o'clock corrosion) can take place. For calculating the rate of corrosion, NORSOK M506 model [Standards Norway 2005] or de Waard and Milliams [de Waard and Milliams 1975; de Waard *et al.*, 1991; de Waard and Lotz, 1993] or similar can be used.

Local

For assessing the rate of "local" corrosion, use the calculated mean value from CO_2 corrosion rate predictive model as the mean rate with coefficient of variance 0.45 in a Weibull distribution.

Uniform

For assessing the rate of "uniform" corrosion, use the (0.4 × calculated mean value from CO_2 corrosion rate predictive model) as the mean rate with coefficient of variance 0.8 in a

Weibull distribution.

Chemical Treatment (inhibitor)

The inhibitor effectiveness should preferably be modelled as a probabilistic distribution, e.g. as a Weibull distribution with nominal efficiency as the mean and coefficient of variance based on an evaluation of the performance in service. As a simplification, the nominal inhibitor factor can be used to reduce the mean corrosion rate used in the Weibull distributions given above.

The hole size distribution due to the degradation by CO_2 corrosion is given in Table A-16.

Table A-17 Hole size distribution in carbon steel piping internally degraded by H_2S

Equivalent Hole Diameter	*% Distribution*	
	Stable ("Leak")	*Unstable ("Burst")*
Small Hole	0	0
Medium Hole	100	0
Large Hole	0	0
Rupture	0	100

A.8.2.5 Internal Corrosion of Carbon Steel Piping - H_2S cracking

All forms of cracking due to H_2S should be prevented by correct materials' selection [EFC 2002a; EFC 2002b; NACE International 2005; NACE International / ISO / ANSI 2001]. If materials and welding are within limits set by these documents, probability of failure = 10^{-5}, otherwise probability of failure = 1.0 and detailed manual assessment will be required.

No further PoF calculations are required. Damage morphology is "cracking". The hole size distribution is given in Table A-17.

A.9 Stainless Steel

A.9.1 External Corrosion of Stainless Steel

Stainless steels have generally good resistance to exposure in marine atmosphere and suffer only incipient corrosion, although local accumulation of salts can lead to severe corrosion, and such areas must be focused during inspection.

Where the stainless steel is insulated, the effect of salt water trapped against the metal can result in pitting at moderate temperatures. At higher temperatures, stress corrosion cracking occurs in some stainless types under conducive conditions: i.e. at areas of high stress, such as welds and heavy cold work. Both local corrosion and cracking must be considered.

A.9.1.1 External Corrosion of Stainless Steel - Uninsulated

Stainless steels generally have good resistance to atmospheric corrosion, but the presence of deposits or crevices can lead to local attack. Inspection should concentrate on identifying locations where such local attack might occur.

Table A-18 Hole size distribution in externally corroded uninsulated stainless steel piping

Equivalent Hole Diameter	% Distribution
Small Hole	100
Medium Hole	0
Large Hole	0
Rupture	0

Uncoated stainless steels can be expected to have a probability of failure of 10^{-4} per mm wall thickness. Note that the excessive presence of deposits, and water traps under clamps, labels etc. should be given special attention and may justify manual evaluation of the PoF.

The coating effectiveness given in Figure A-2 can be used to reduce the estimated probability of failure by multiplying the uncoated probability of failure with a factor equal to (100 – *Effectiveness*)/100.

The hole size distribution should be taken as given in Table A-18.

A.9.1.2 External Local Corrosion of Stainless Steel - Insulated

This mechanism presents itself on stainless steels as apparently randomly distributed pits, albeit typically more predominant at welds, and is associated with saline water retained by insulation, deposits, etc. The probability of failure increases markedly with temperature, depending also on the type of stainless steel. Control of temperature is thus important. Attention should also be paid to excluding water, by effective waterproofing of the insulation. A coating on the steel will reduce probability of attack, but the deterioration of coating over time must be considered. After removal of the insulation, detection can be made by visual or dye penetrant examination of the surface. Once pitting has initiated it can progress rapidly to failure. Note that this type of damage is expected to arise under similar circumstances as External Stress Corrosion Cracking.

The onset of local corrosion is controlled by temperature, given that the conducive conditions are present. The probability of failure per unit wall thickness for the different materials is given as a function of temperature in Figure A-5. The hole size distribution is given in Table A-19.

1) Select curve for material in Figure A-5. Read off failure probability for given temperature.
2) Divide result by wall thickness in mm, to give PoF.
3) The coating effectiveness given in Figure A-2 can be used to reduce the estimated probability of failure by multiplying the uncoated probability of failure with a factor equal to (100 – *Effectiveness*)/100, with a minimum of 10^{-5}.

Stress corrosion cracking can also occur in stainless steels at elevated temperatures. Inspection of the insulation condition itself is a very important means of controlling damage under insulation.

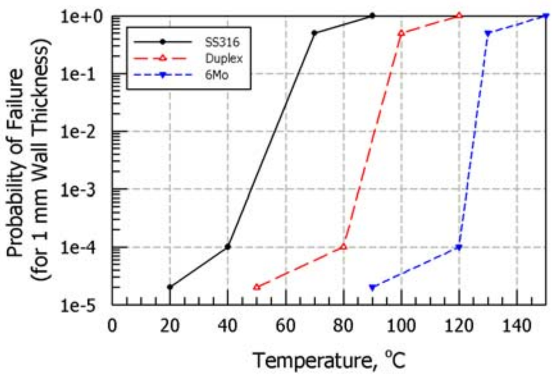

Figure A-5
PoF for local corrosion of stainless steel under insulation

Table A-19 Hole size distribution in externally and locally corroded insulated stainless steel piping

Equivalent Hole Diameter	*% Distribution*
Small Hole	100
Medium Hole	0
Large Hole	0
Rupture	0

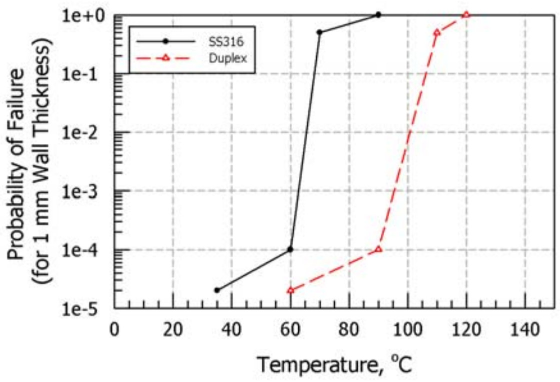

Figure A-6
PoF for ESCC of stainless steel under insulation

Table A-20 Hole size distribution in externally and ESCC corroded insulated stainless steel piping		
Equivalent Hole Diameter	*% Distribution*	
	Stable ("Leak")	*Unstable ("Burst")*
Small Hole	0	0
Medium Hole	100	0
Large Hole	0	0
Rupture	0	100

A.9.1.3 External Stress Corrosion Cracking (ESCC) of Stainless Steel - Insulated

This appears as cracking in areas with high tensile stresses, typically at welds, and is associated with salt water retained by insulation. The probability of failure due to ESCC increases markedly with temperature, but is dependent on the type of stainless steel; thus, control of temperature is important. Attention should also be paid to excluding water, by effective waterproofing of the insulation. A coating on the steel will reduce probability of attack, but the deterioration of coating over time must be considered. After removal of the insulation, detection can be made by visual or dye penetrant external examination. Note that once ESCC has been initiated, it is expected to progress rapidly to failure, and inspection is therefore not suitable for monitoring defect development.

The onset of ESCC is controlled by temperature, given that the conducive conditions are present. The probability of failure for different materials is given as a function of temperature in Figure A-6, with the hole size distribution given in Table A-20. Note that material type 6Mo is not included in the figure: there are suggestions that ESCC may be possible at elevated temperatures. If possible, a specialist should be consulted if this is cause for concern.

The coating effectiveness given in Figure A-2 can be used to reduce the estimated probability of failure by multiplying the uncoated probability of failure with a factor equal to (100 – *Effectiveness*)/100.

Before concluding on hole size, an assessment of leak-before-break should be made, as duplex stainless steels may suffer a toughness transition when subjected to low temperatures – such as may be found during blow-down. This may lead to a rupture of the part. Otherwise, the high toughness generally found in stainless steels will prevent unstable fracture.

A.9.2 Internal Corrosion of Stainless Steel

A.9.2.1 Internal Corrosion of Stainless Steel - Water

This presents itself as pitting on stainless steel primarily at welds and in crevices, such as at screwed connections. Control can be by monitoring temperatures and water chemistry, as increased temperature, increased salt content and increased oxygen content will increase the likelihood of pitting. Inspection can be by visual, radiography or dye penetration of accessible surfaces. Once damage has been initiated, it will progress rapidly to failure and is therefore not suitable for inspection.

Degradation of stainless steels in water results in local attack, typically pitting or crevice corrosion, the onset of which is assumed to be controlled by temperature, given that the water conditions are as specified in Table A-6. The probability of failure per unit wall thickness for the different materials and water types is given as a function of temperature in Figure A-7. The hole size distribution is given in Table A-21.

The assessment procedure is as below:

1) Select appropriate water category in Table A-6.
2) Select curve for material in Figure A-7. Read off failure probability for given temperature.
3) Divide result by wall thickness in mm, to give PoF.

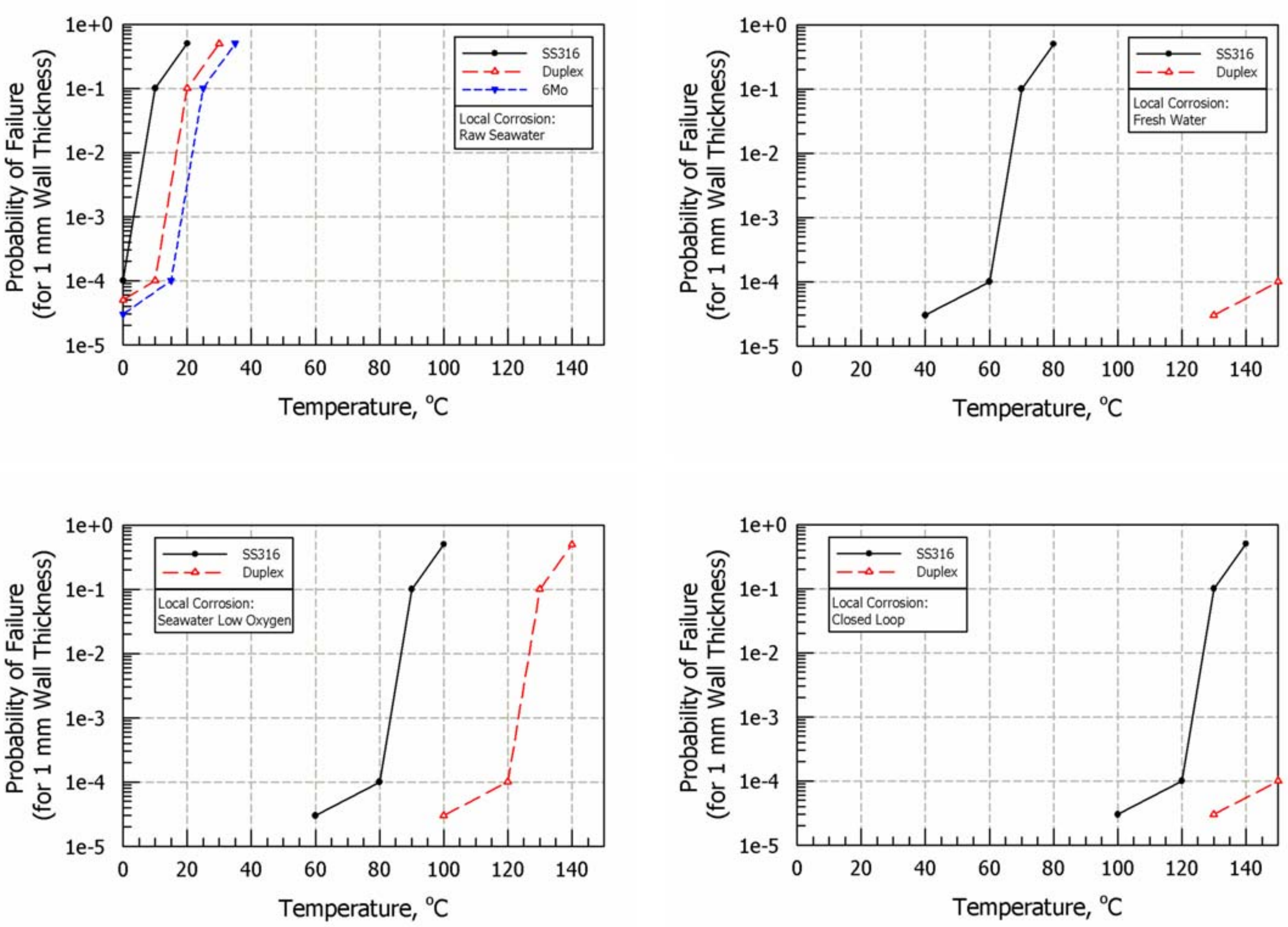

Figure A-7
PoF by water category for stainless steels

Table A-21 Hole size distribution in stainless steel piping internally degraded by aqueous corrosion	
Equivalent Hole Diameter	*% Distribution*
Small Hole	100
Medium Hole	0
Large Hole	0
Rupture	0

A.10 Copper-nickel Alloys

A.10.1 External Corrosion of Copper-Nickel Alloys

A.10.1.1 External Corrosion of Copper-Nickel Alloys - Uninsulated

Most of the copper-nickel alloys are resistant to corrosion in marine environment, hence, no external degradation is expected. So a fixed probability of failure of 10^{-5} should be assigned.

A.10.2 External Corrosion of Copper-Nickel Alloys - Insulated

Most of the copper-nickel alloys are resistant to corrosion under insulation, hence, no external degradation is expected. So a fixed probability of failure of 10^{-5} should be assigned.

A.10.3 Internal Corrosion of Copper-Nickel Alloys

A.10.3.1 Internal Corrosion of Copper-Nickel Alloys - Water

Many copper-based alloys have good or reasonable corrosion resistance to quiet seawater, but high rates of corrosion (erosion-corrosion) can occur in flowing seawater. This is probably due to a loss of protective scale as a result of shear stress at the liquid-scale interface, and increased oxygen concentration at the surface. The corrosion rate increases with an increase in temperature and increase in the amount of particulate matter in the water.

While little corrosion is expected in desalinated and potable water categories, at times stagnant conditions supporting sulphate-reducing bacteria, can lead to high local corrosion rates.

This corrosion-erosion is not limited to bends and may occur in straight sections also. The damage can be detected by wall thickness measurements made by ultrasonic testing (UT) of the area,

Determine the probability of failure as follows:

1) If flow rate is above 2 m/s then set PoF =1.0 and refer to a specialist.
2) Identify water category from the systems and water categories in Table A-6.
3) If materials are not included in Table A-1, then set PoF =1.0 and refer to a specialist.

4) Select mean rate and standard distributions, as directed in Table A-22.
5) PoF is calculated using the “uniform” damage morphology.
6) Select hole sizes as given in Table A-23.

Table A-22 Corrosion rates in copper-based alloy piping by different categories of water

Material Type	*Condition*	*Mean (mm/year)*	*Standard Deviation (mm/year)*
Raw Seawater	Flow rate < 1 m/s	0.08	0.01
	Flow rate > 1 m/s	0.2	0.1
Seawater + Biocide / Chlorination	Flow rate < 1 m/s	0.08	0.01
	Flow rate > 1 m/s	0.2	0.1
Seawater Low Oxygen		0.02	0.02
Seawater Low Oxygen + Biocide		0.02	0.02
Seawater Low Oxygen + Chlorination		0.02	0.02
Seawater Low Oxygen + Biocide + Chlorination		0.02	0.02
Fresh water		0.015	0.05
Closed loop		0.015	0.05
Exposed Drains	Flow rate < 1 m/s	0.08	0.01
	Flow rate > 1 m/s	0.2	0.1
Sanitary Drains		0.05	0.05

Table A-23 Hole size distribution in copper-based alloy piping internally degraded by aqueous corrosion

Equivalent Hole Diameter	*% Distribution*
Small Hole	0
Medium Hole	0
Large Hole	100
Rupture	0

A.11 Titanium

A.11.1 External Corrosion of Titanium

A.11.1.1 External Corrosion of Titanium - Uninsulated

No external degradation of titanium is expected in marine environment, so a fixed probability of failure of 10^{-5} should be assigned.

A.11.2 External Corrosion of Titanium - Insulated

No corrosion under insulation of titanium is expected, so a fixed probability of failure of 10^{-5} should be assigned.

A.11.3 Internal Corrosion of Titanium

A.11.3.1 Internal Corrosion of Titanium - Water

No degradation of titanium is expected in the water categories described, so a fixed probability of failure of 10^{-5} should be assigned. To facilitate calculation of consequence the hole size distribution should be considered as given in Table A-24.

Table A-24 Hole size distribution in titanium piping internally degraded by aqueous corrosion

Equivalent Hole Diameter	*% Distribution*
Small Hole	100
Medium Hole	0
Large Hole	0
Rupture	0

A.12 Fibre Reinforced Polymer

Design, fabrication, installation and testing should be carried out in accordance with FRP piping specifications; supports for pipe and heavy fittings, jointing design and construction should be checked. FRP piping is susceptible to mechanical damage due to being stood on, used as a support for ladders, and damage due to welding spatter falling from welding and cutting operations. In addition, FRP is susceptible to degradation of the polymer matrix due to exposure to ultraviolet radiation from sunlight and welding.

In the absence of sound degradation models, and unless the analyst has access to experience with FRP, it is recommended that FRP is allocated a low reliability, i.e. PoF =1.0, and calculated on this basis. This focuses resultant high risk equipment for assessment by specialists.

The hole sizes for FRP required to calculate consequences are given in Table A-25.

Table A-25 Hole size distribution in FRP piping internally degraded by aqueous corrosion

Equivalent Hole Diameter	*% Distribution*
Small Hole	0
Medium Hole	0
Large Hole	0
Rupture	100

A.13 Summary of Some External Degradation Mechanisms

Table A-26 External corrosion descriptions

Mechanism	*Material*	*Morphology*	*Inspection Guidance*
Atmospheric Corrosion	Carbon steel	Patches of damage leading to smaller size holes. Usually associated with coating damage and deterioration. Enhanced in areas where wetting is prolonged, including condensation. Significantly greater degree of corrosion can take place around supporting clamps.	Minimum surveillance is required to periodically confirm initial assumptions, particularly coating condition.
	Stainless steels Nickel-based alloys	Incipient attack, but small size holes associated with local attack where geometry allows damp salts to collect.	Visual surveillance is required to check conditions. Attention focused on geometry, clips, supports, etc. that can collect water and promote crevice attack. Coatings, if used, should be checked.
	Titanium	No damage expected.	Minimum surveillance.
Corrosion Under Insulation	Carbon steel	Damage as patches of attack where water can collect in insulation. Coatings may be used.	Damage controlled by water ingress through insulation. Deterioration of any coating will affect overall resistance. Visual inspection of weather protection, for leaks to locate potential areas. RT and UT can be used for sizing and monitoring.
	Stainless steels Nickel-based alloys	As above, welds likely to have lower resistance that parent material. Coatings may be used.	As above. Monitoring of damage by inspection is not recommended, due to rapid growth period. Corrective maintenance, for damage and preventative maintenance, of weather protection systems, is more important.
	Titanium	No damage expected.	Minimum surveillance.
External Stress Cracking Under Insulation	Stainless steels (not 6Mo type)	Surface cracks where water can collect at elevated temperatures under insulation. Welds particularly susceptible.	Damage controlled by water ingress through insulation. Deterioration of any coating will affect overall resistance. Visual inspection of weather protection, for leaks to locate potential areas. PT, RT and UT can be used to find cracks. Monitoring of damage by inspection is not recommended, due to rapid growth period. Corrective maintenance for damage and preventative maintenance of weather protection systems are more important.

APPENDIX B
FATIGUE ASSESSMENT

B.1 External Mechanical Damage

Mechanical damage caused by vibration, ship/platform movement, flow effects, or other sources, may cause fatigue crack growth and fracture. For piping systems, the damage is often located in local hot-spots, such as welded connections, branches, clamps, or vessel nozzles, where the design or fabrication gives a high stress concentration factor and restraint may also increase loading locally.

Fatigue in piping systems caused by high frequency vibrations (such as from reciprocating machinery) is expected to propagate rapidly to failure once a crack is initiated, and is therefore not readily amenable to monitoring and control by inspection. In such situations, it is recommended that the local vibration amplitude and the local stresses are measured, rather than calculating the crack growth.

Where the source of vibration is low frequency, such as from ship motion, then inspection may be used to measure the development of damage.

B.2 Introduction

The failure probability due to *fatigue* and *fracture*, caused by high and low frequency fatigue is assessed for a given component, based on its geometry, dimensions, materials of construction, loading and other operational conditions.

Note:

This document differentiates between high and low frequency fatigue and not high and low cycle fatigue.

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B.2.1 Fatigue

What distinguishes fatigue from other failure mechanisms is the uncertainty with respect to cumulative damage. In a weld-defect free, thin-wall thickness piping system, subject to high frequency stress ranges, virtually all of the fatigue life is spent in the so-called initiation phase, where any direct measurement of the progress is impossible. In the subsequent crack growth phase, the time for the crack to travel through the thickness may be short. Hence, for this case of fatigue, it is not feasible to measure the remaining life, as one can do, for example, for through thickness corrosion, where techniques of measurement exist. Therefore, high frequency fatigue is classified as a “susceptibility” type degradation mechanism.

However, various techniques are in existence to detect and measure the size of fatigue cracks that are growing, provided they are below a certain depth. Due to the difficulty in measuring fatigue crack initiation, one has to resort to indirect measurement, in combination with evaluation of contributing factors.

Indirect measurement of fatigue is obtained by measurement of stress ranges subjected to the structural part in question. With the fatigue-life diagram (S-N curve – graphical presentation of the dependence of fatigue life, N, on fatigue strength, S) as reference, the effect of stress range on fatigue life is evident. Stress concentration, caused by geometrical shapes, both locally and globally, contribute to fatigue as they locally amplify the stress ranges experienced by the material. It is possible to distinguish and quantify such geometrical factors with respect to inspection methodology.

Due to the long time taken for crack initiation in a defect-free section, compared to that for crack growth, it is crucial that the pipe welds are defect-free to ensure adequate system fatigue life. If welding flaws are present, the benefit of a long initiation phase may be lost and therefore the fatigue lifetime of the joint very much reduced. Such flaws may be introduced during the construction phase, as a result of sub-standard welding and inspection.

B.2.2 High Frequency Load Ranges

With load ranges acting on components at more than 1×10^7 cycles per year, or approximately 0.3 Hz, cracks may grow rapidly to critical crack size. The time interval between the crack reaching a size where its probability of detection by inspection is high, and the crack reaching a critical size where leakage or unstable failure occurs, is very short – it can be in the order of weeks. Fracture mechanics crack growth analyses are of little use and high frequency fatigue can be considered as a “susceptibility” model (there is either an intact pressure boundary, or a failure is imminent), and so is not amenable to measurement or monitoring the crack size by inspection. The approach used for other susceptibility models in the Recommended Practice is adopted, whereby measuring of the controlling parameters is recommended in place of NDT.

The physically measurable quantities of interest are the vibration velocities, stresses (strains) in the piping, and flaw sizes in welds. The strain can further be converted to stress and compared to appropriate S-N curves.

B.2.3 Low Frequency Fatigue

Low frequency cyclic loading, such as that caused by ship/platform motions, infers a crack growth duration that is sufficiently long to allow monitoring by NDT. An approach using S-N curves or fracture mechanics analyses can be applied to determine when to inspect.

B.2.4 Practical RBI Assessment of Fatigue

A guideline for a simplified assessment of potentially fatigue-prone welds is presented in this section. As the problem of fatigue cracking is generally concentrated at welded joints, those are therefore the focus of this work. Other joining methods, such as adhesive or bolted joints, are not considered here. The guideline covers how to distinguish fatigue-prone welded joints of inadequate quality from welded joints of adequate quality, by simple and fast visual examination methods. The guideline also covers how remedial work shall be carried out in order to modify inadequate welded joints to become adequate with respect to fatigue susceptibility.

Measurement and analysis of fluctuating stress ranges are also included.

This simplified fatigue evaluation guideline is a “go/no-go” type of assessment, and it has been a clear goal that the assessment of the welded joints shall be quick and not require extensive training or equipment.

For the purpose of the guideline, the categorisation of welds as “adequate” or “inadequate” has been introduced. It is recommended that risk-based methods be used for ranking and determining where to concentrate the efforts.

B.3 Quantification of Probability of Failure in Thin-walled Pipe

It is not feasible to adequately quantify a probability of failure in a thin-wall piping system subject to high frequency fluctuating stresses. This is due to the long initiation phase, which determines the actual fatigue life of the structure and is difficult to measure or predict, compared to the short time to failure once a crack is present. This can be seen in Figure B-1, where fracture mechanics’ calculations have been used to demonstrate potential crack depth as a function of time under several loading conditions. These curves show that, by the time the defect is of a size where the probability of detection suggests that it might actually be detected (of the order of 2 to 4 mm), the remaining time to failure is in the order of weeks or days. For this reason, therefore, the degradation mechanism of high frequency fatigue is given as “susceptibility”.

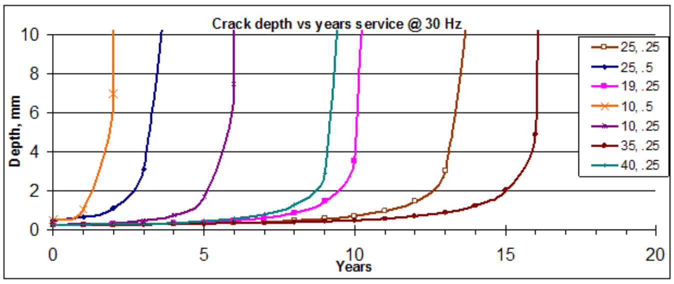

Figure B-1
Fatigue crack depth as a function of time for several stress ranges and initial defect sizes

Whether fatigue failure occurs is governed by the (measurable) stress ranges and indeed by the contributing geometrical factors, which can be evaluated. It should be safe to say that the latter are the cause of the majority of fatigue failures experienced in hydrocarbon processing plants to date.

The typical conditions that apply when fatigue failure is possible are moderate stresses, combined with contributing geometrical factors, and flaws or defects.

High stress ranges will cause overload failures rather than fatigue failures. Overload failures, and low-cycle fatigue failures, are generally not influenced by geometrical stress amplifiers. Hence, the geometrical contributing factors are the most important to address in the case of fatigue failures that do not occur immediately.

B.4 S-N Curves

The assessment assumes that an adequate S-N curve is available for the material and joint configuration in question. To date, this is most likely not the case if the pipe system is of a corrosion resistant alloy. Previous test work by DNV indicates that such materials render the pipes more fatigue resistant than equivalent geometries in carbon steel.

However, the use of an over-conservative S-N curve may produce the initiation of unnecessary remedial work, or additional support that may transfer the problem or create new problems. DNV therefore recommends that, where the use of over-conservative S-N data is likely to give an excessive number of remedial actions, the missing S-N data should be obtained by a method analogous to the DNV work referred to above, at least as limited verification points to indicate the presence of the relevant S-N curve.

The acceptance criterion for stress ranges used in the draft guideline is taken from a recommendation from The Welding Institute [Gumey 1976] that if all stress ranges are below the range corresponding to 10^7 cycles, then fatigue need not be considered. For a stress range spectrum including ranges above this value, stress ranges corresponding to less than 2×10^7 cycles are considered not to contribute to fatigue in a Miner-Palmgren type of cumulative assessment. The guideline does not consider cumulative assessments of stress spectra where different stress ranges contribute differently to fatigue crack initiation. The simplified approach of this guideline is to state that all stress ranges should be below the limit for contribution to fatigue crack initiation.

B.5 Assessment for Fatigue

The guideline below introduces and describes the assessment cycle, which is given as a flow-chart route that shows the required sequence of prioritised actions.

B.5.1 Application of the Guideline

This guideline is provided as a tool to quickly identify and perform remedial work on welds that are potentially fatigue-prone by surface crack initiation (and growth).

It does not cover measures against failure due to insufficient material thickness.

Guidance note:

— Potentially fatigue-prone welds are typically welds that join an oscillating mass to a firm structure, such as valves on branch pipes fitted to main flow pipes.
— Insufficient material thickness may result in overload failure or low-cycle fatigue failure. These failure modes are generally not sensitive to inadequacy as defined herein.
— This guideline is based on distinction between welded joints that are either:

  — adequate
  — inadequate.

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In the case of inadequate welds that are subjected to fatigue loading, remedial action must be taken if failure is unacceptable.

B.5.2 Definitions

The following definitions are used in this guideline:

Term	*Definition*
Adequate joint	A welded joint that has the sufficient smoothness and manufactured surface quality to withstand fatigue loading without crack initiation from the surface.
Assessment cycle	The complete work process for each critical area.
Check points	Defined areas of the welds in which to concentrate the close, visual inspection.
Close visual inspection	Visual inspection for surface defects for selected, individual, welded joints.
Criteria	Criteria apply to undercut, bulge and grinding marks, which are factors that increase the likelihood of fatigue crack initiation from the surface.
Critical area	Area where the consequence of failure is unacceptable.
Direction of viewing	How to orientate the view to get the best ability to detect criteria.
Evaluation	Comparing the occurring fluctuating stresses with the appropriate S-N curve.
General visual inspection	A survey to get the overview of the critical area to know where to prioritise the close inspections within that critical area.
Inadequate joint	A welded joint that does not have the sufficient smoothness and manufactured surface quality to withstand fatigue loading without crack initiation from the surface.
Joint remedial work	Modifying the appearance (i.e. geometry and surface) of the weld in order to change its condition from inadequate to adequate quality.
Ranking (1)	In order to determine where to start the work, critical areas are ranked with respect to consequence of failure.
Ranking (2)	In order to prioritise within a critical area, joints are ranked based on the severity of the configuration before close inspections are carried out.
Remedial action	Modification work carried out to change the status of a welded joint from inadequate to adequate.
Types of welded connections	Based on configuration, the connections are of either type A, B or C.
Visual examination	Using the human eye to distinguish an inadequate welded joint from an adequate welded joint based on criteria.

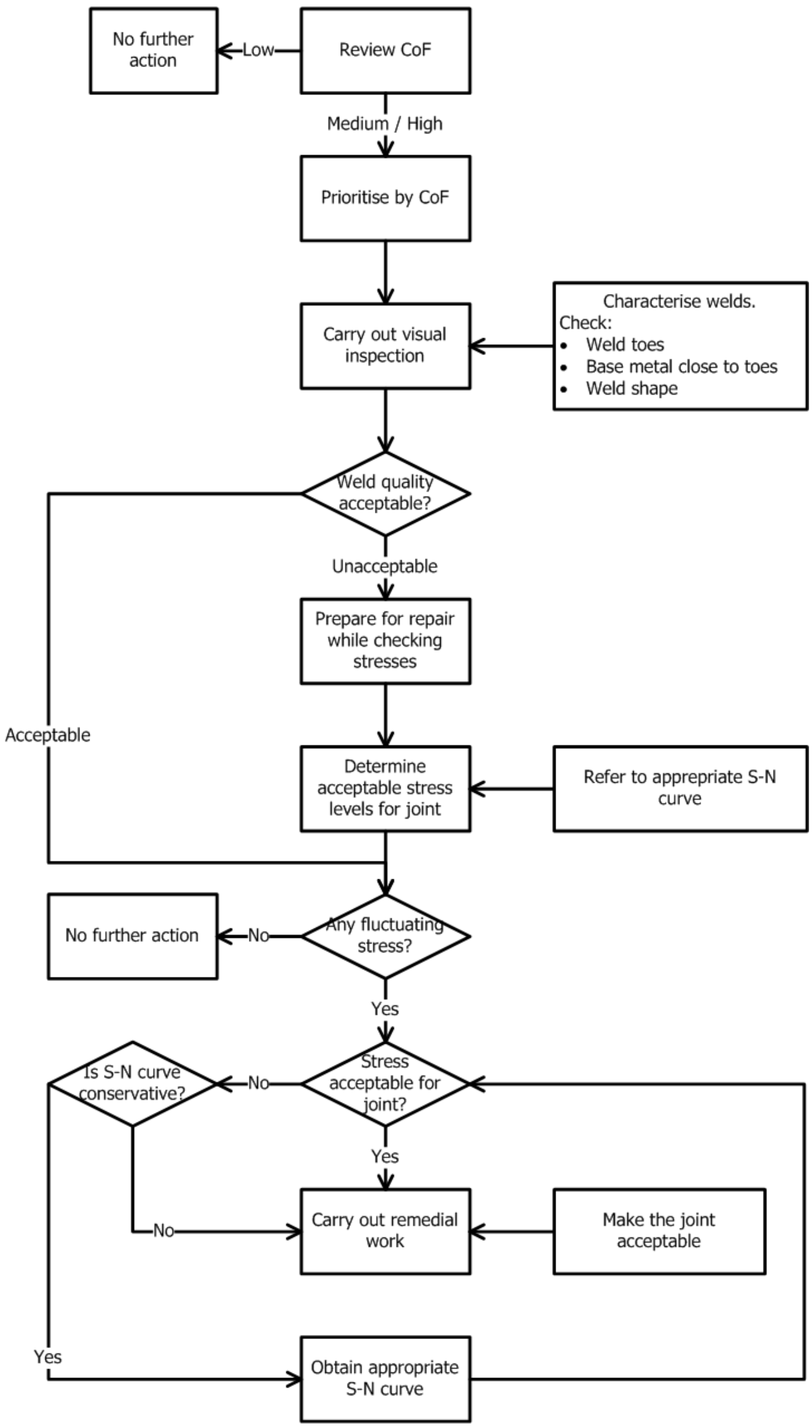

Figure B-2
The assessment cycle for a critical area

B.5.3 The Assessment Cycle

The assessment cycle is shown graphically in Figure B-2. Consider whether it is most effective to carry out all ranking and inspection planning activities before beginning inspection.

B.5.3.1 General Inspection

Identify the potentially susceptible areas of the process plant, and rank them in order of severity with respect to consequence.

Start with the area with the most severe consequence, and perform a general visual inspection. As part of the inspection, check the presence of welded branches on the P&ID and isometric diagrams, and highlight the welds of least favourable profile on the piping diagram.

Make a general ranking of the connections with respect to mass size and branch pipe size.

Guidance note:

— For the connection weld joint of a branch pipe with an attached mass:

  — a heavy mass is worse than a light mass
  — a small diameter is worse than a large diameter.

— A small diameter branch pipe connected to a large diameter main pipe is worse than a large diameter branch pipe to a small diameter main pipe.

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B.5.3.2 Close Inspection

In order to determine whether a joint is adequate or inadequate for fatigue service, close inspections will have to be carried out for each critical area.

Start with the most severe combination of mass to branch size, and branch size to main pipe size, and perform the first close inspection here.

Guidance note:

If the number of joints is limited, it may be more efficient to skip this ranking and just start the close inspections immediately after the survey inspection.

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B.5.3.3 Types of Welded Connections Covered

A. Straight pipe-to-pipe welds.
B. Pipe-to-pipe branch connections.
C. Welded pipe supports.

B.5.3.4 Check Points, All Connections

I. Weld toe.
II. Base metal close to weld toe.
III. Shape of weld.
Additional check points for connection C:
IV. Corners.

B.5.3.5 Criteria

I. No visual undercut permissible.
II. No grinding marks at weld toe with other orientation than perpendicular to the weld toe.
III. No bulge on weld material to give angle above 45° at the weld toe.
IV. Special attention needed.

B.5.3.6 Method

Perform a visual examination of each weld at the check points shown in Figure B-3 to Figure B-8. Use only visual methods, and look from different angles to get the best view for the defect in question. Create a shade or apply a torch as applicable to reduce or increase the amount of light as required to get a good view. Use a mirror in case of restricted access to all sides.

Conclusion

— If this visual inspection does not detect any defects as given in this section, the weld joint is deemed adequate.
— The check points are shown in Figure B-3 to Figure B-8.
— Due to the shape of the corners, inspection viewing must be carried out from both sides for all four corners.
— All of the weld must be inspected.

B.5.3.7 Direction of Viewing

This screening method is based on fast, visual inspection. In order to get the right results, the direction of viewing must be applied. The following viewing directions must be applied:

I. Weld toe undercut:
Direction of viewing parallel to weld toe.
II. Pipe surface condition:
Direction of viewing perpendicular to surface.
III. Weld cap profile:
Direction of viewing parallel to weld toe and weld.
IV. Corners:
Same as I, II and III, but in two directions:

— Parallel to support.
— Perpendicular to support.

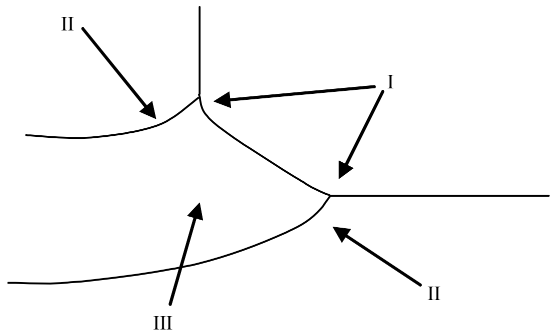

Figure B-3
Inspection points for branch weld

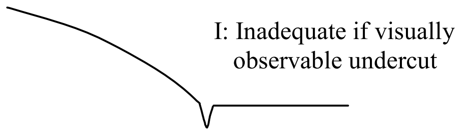

Figure B-4
Weld toe undercut

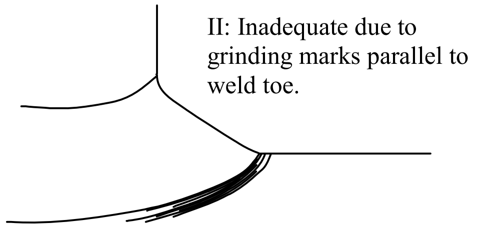

Figure B-5
Ground base metal at weld toe

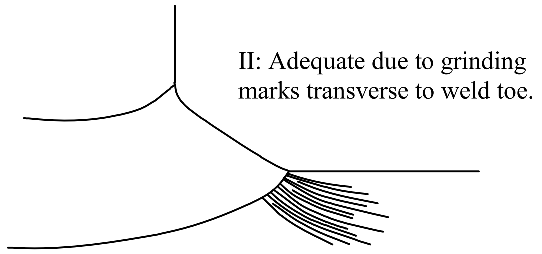

Figure B-6
Ground base metal at weld toe

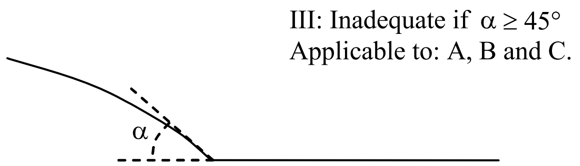

Figure B-7
Weld metal cap profile

IV: Special attention to corners. View from both sides.

In this sketch, arrows indicate directions of viewing.

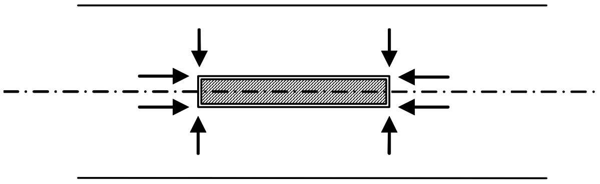

Figure B-8
Special attention to corners on welded supports

B.5.4 Measurement of Stresses

In order to evaluate whether fatigue may occur, the applied stress ranges must be measured.

Important notice:

— Due to the stress amplification of inadequate geometry, any inadequate welds should be modified to an adequate condition before proceeding to measurement of stresses.
— Visual observation of vibration levels may be misleading; hence an appropriate transducer must be used.

Guidance note:

If surface temperature permits, hand held frictional strain gauges can be used with good results. Alternatively, clip-on extensometers may be used as well as permanently applied strain gauges.

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B.5.4.1 Location of measurement

Stresses shall be measured 15 mm away from the weld toe.

Guidance note:

— Any other location of measurement may impair the results.
— The gauge length of the transducer shall be orientated perpendicular to the weld toe.
— Measurement closer than 10 mm, or on or across the weld itself, will not provide results that can be used at all.
— The measurements shall be made on both sides of the weld, or at the side of the weld that is considered of importance. Several directions shall be measured as applicable.

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B.5.5 S-N Curve Selection

Measured stress levels must be compared to an acceptance criterion.

The acceptance criterion for permissible stress range is derived from the appropriate S-N curve, at 10^7 cycles [Gumey 1976].

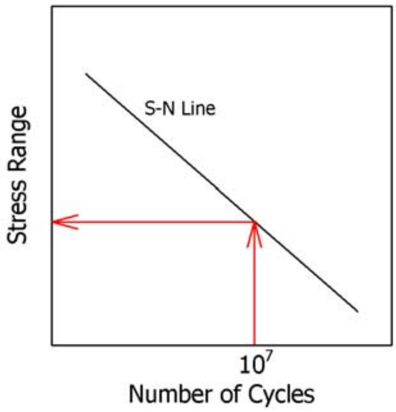

Figure B-9
Determining the highest permissible stress range from the S-N diagram

Evaluation

If an S-N curve is available for the actual material and geometry in question, then it should be used.

If such an applicable S-N curve is not available, select a fatigue curve from DNV-RP-C203 [DNV 2005a], based on principal geometry and loading picture.

Guidance note:

An alternative relevant publication to DNV Classification Note 30.2 [DNV 1984] may be used instead.

This assumes that the weld has an adequate condition.

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Important notice:

— Ensure that stress concentration from weld geometry is covered by the fatigue curve chosen as appropriate.
— Additional stress concentration from global geometry (configuration) must be taken into account when comparing the measured stress level to the S-N curve.
— If measured stresses are higher than the acceptance criterion, stresses must be reduced, or if possible a more appropriate S-N curve for the material and geometry in question should be used for a re-assessment.

B.5.6 Joint Remedial Work

Any inadequate joint must be upgraded to adequate quality.

Important notice:

— Joint remedial work shall be carried out as described either herein, or in instructions provided, such as welding procedures, repair procedures etc.
— No flame-cutting or other unsolicited methods are permissible.
— Due to the uncertain nature of re-supporting, joint remedial work shall always be carried out if fluctuating stresses are present.

Guidance note:

— Introducing additional supports without performing joint remedial work is ineffective. It may not solve the problem, and the likelihood of new problems is high.
— If stresses are above the acceptance criterion, then additional supporting work or other modifications should be carried out in addition to joint remedial work.
— If such additional work is performed, the assessment cycle must be repeated for the affected area.
— Joint remedial work is categorised by the defects the work is remedy for.

I. Undercut at weld toe.
II. Grinding marks in parallel with the weld toe.
III. Excessive weld cap profile.

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B.5.6.1 Removal of Undercut

Visually observable undercut is removed by grinding or dressing. This process shall leave all marks transverse to the weld toe.

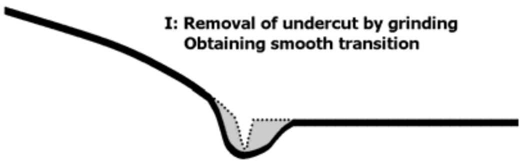

Figure B-10
Weld toe undercut removal

Guidance note:

If repair grinding marks are not left perpendicular to the weld toe, the situation may be worse after the repair.

Undercut must not exceed 10% of the initial wall thickness after grinding or dressing.

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B.5.6.2 Removal of Grinding Marks in Parallel with the Weld Toe.

Grinding marks in parallel with the weld toe shall be removed by grinding or dressing which leaves the marks transverse to the weld toe.

B.5.6.3 Excessive Weld Cap Profile

Excessive weld cap material shall be removed by grinding, leaving the finishing grinding marks transverse to the orientation of the weld.

Guidance note:

If there is insufficient weld material present to perform the required joint remedial work, then more weld material must be added in accordance with the appropriate welding procedure.

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APPENDIX C
COF ASSESSMENT

C.1 Understanding CoF

C.1.1 Introduction

Consequence of failure (CoF) is defined for all consequences that are of importance to the operator, such as safety, economy and environment. For the purposes of RBI, the consequence of failure is defined as the outcome of a leak given that the leak occurs.

Table C-1 gives an overview of the factors to consider when evaluating the consequence of failure. In order to further appreciate the different aspects which need to be considered when carrying out a consequence analysis, some important principles are presented below.

The consequences of a release that leads to a fire or explosion demand different consideration from a release of a fluid or gas that does not ignite. It is common practice to address the consequence calculations for ignited and unignited releases separately and hence their different outcomes with respect to safety, economic and environmental consequences.

It is common practice to evaluate such consequences based on leak rates. Leak rates are closely related to leak hole sizes, and leak hole sizes are again dependent on degradation mechanisms. Evaluations based on this type of information ensure that the estimated consequences can more fully reflect the actual circumstances of the leak. Expected hole size distribution may vary from a “pinhole”, to a complete breach of the component, depending on the degradation mechanism.

Table C-1 Factors to consider in consequence assessment

Ignited leak		
Safety Consequence	*Economic Consequence*	*Environmental Consequence*
Consider loss of life due to: — burns to personnel — direct blast effects to personnel — indirect blast effects to personnel (missiles, falling objects) — injuries sustained during escape and evacuation.	Consider the costs of: — repair of damage to equipment and structure — replacement of equipment and structural items — deferred production — damage to reputation.	Consider the effects of: — toxic gas release — smoke.
Unignited leak		
Safety Consequence	Economic Consequence	Environmental Consequence
Consider loss of life due to: — toxic gas release — asphyxiating gas release — impingement of high pressure fluids on personnel.	Consider the costs of: — deferred production — repairs.	Consider the effects of: — hydrocarbon liquids spilled into the sea.

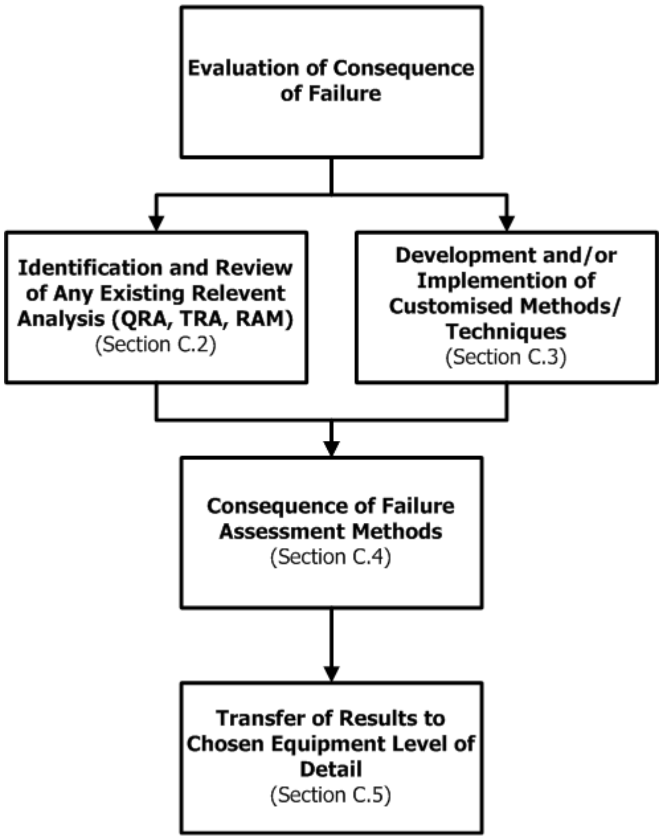


Figure C-1
Overview of CoF working process

C.1.2 Evaluation of Consequence of Failure

The recommendations are based on working at assessment/ equipment levels of details 1 and 2 (system level and ESD-segment level) before transferring results to a lower assessment/ equipment level of detail. Figure C-1 illustrates the process of evaluating the consequences of leaks.

C.1.3 System Review, Description and Modelling

This involves the review, description & modelling of the following (the first two points below are mostly relevant for safety - personnel and environment - whereas point 3 is relevant for economic consequences):

— *Modules*. Topsides of offshore installations are usually built with discrete modules or levels, having specific functions, and active and passive barriers that contain or mitigate effects of failures. It is therefore general practice to address the consequences for each “module”. For each module, key parameters are:

  — the dimensions
  — the ventilation rates (natural or forced)
  — the type of barriers (walls, floor) applied. In particular the explosion and fire resistance of the barriers needs to be reviewed
  — the number of ignition sources in the modules (“equipment count”), in particular the number of pumps, compressors and generators
  — the number of hot work hours in relation to actual platform practices
  — configuration with regard to isolatable sections (see next bullet point).

— *Isolatable Sections*. The isolatable section (or inventory group) is associated with the (maximum) amount of hazardous fluid that can be released in the event of a leak. The amount of hazardous fluid contained in an isolatable section depends on the inventory of process equipment and piping, and the location of emergency shut-in valves. These valves (Emergency Shutdown Valves, or ESDVs) serve to isolate a leak and hence contain the release of hazardous fluid. ESDVs are generally found at the import and export risers, and at strategic locations, e.g. to isolate the separator(s), and the gas compression section. For each isolatable section a representative fluid will need to be chosen, i.e. the accidentally released fluid that will be evaluated. A fluid is evaluated as flammable or toxic, but it must be noted that some fluids (e.g. hydrogen sulphide) are both flammable and toxic. Also, some fluids are mixtures (e.g. methane, ethane, carbon dioxide and hydrogen sulphide), which require the use of "representative fluids". Care must be taken in selecting the appropriate representative fluid, in particular when a predominantly flammable mixture (e.g. well gas) has a high concentration of toxic fluid (e.g. hydrogen sulphide). In case the fluid is a mixture of hydrocarbons, it is recommended to use the hydrocarbon with highest mol%, or a "weighted" hydrocarbon based on the average molecular weight of the mixture.

— *Deferred production profiles*. The amount of deferred production will depend strongly on the design of the installation process system(s) and their interaction. Production systems with several parallel trains can usually be operated with one train isolated so that the installation will be able to produce at a reduced rate until the damaged train is repaired and re-commissioned. This review involves reviewing the production process from well to export facilities, and determining what the effect on production would be if a leak arose in each section of piping and each piece of equipment, and developing the deferred production profiles on this basis. Utilities' systems should be included because in many cases their failure will cause failure of the process (e.g. water injection, instrument air, chemical injection) or require shutdown (e.g. unserviceable firewater).

C.1.4 Mass Leak Rates for Gas and Oil

The leak rate is a function of the fluid released (oil or gas), phase, pressure and temperature. Mass leak rates (or release rates) are given as a function of pressure and hole size in Figure C-2 and Figure C-3, for gas and oil respectively, based on representative fluid and gas densities. From the figures it can be concluded that the release rates are substantially affected by the hole size. This is the reason why separate event trees are developed for different hole sizes.

Once the leak rates have been determined, the next step is to model the dispersion of fluid. Pressurised gaseous releases will mix with air; liquid releases can form aerosols (spray release) or form as pools, which could evaporate. Dispersion is required in order to form a flammable or toxic vapour cloud which affects personnel and equipment. Dispersion calculations generally require the use of detailed computer simulation models needing input concerning, for example, the volume of the module, the air change rate, the density of the leaking fluid and the flash fraction. The volume of the module can be corrected for major "obstacles" present in the module (e.g. separate rooms, large equipment). If the module is mechanically ventilated, the air change rate can be based on the design capacity of the HVAC system. If the module is naturally ventilated, the air change rate is often a function of the geometry of the module, wind speed and predominant wind direction. Flash fraction refers to the fraction of volume released that is gas phase, and is therefore equal to 1 for gas. The value for oil will depend on the fraction of gas within the process stream.

For more information, especially regarding safety consequences, see ISO 17776. It presents different tools and techniques for identifying and assessing hazards and risks. It also refers to a number of useful documents that supply more detailed information on certain issues. It is also useful to review any available QRAs, and preferably from different suppliers as QRAs can be carried out in many different ways.

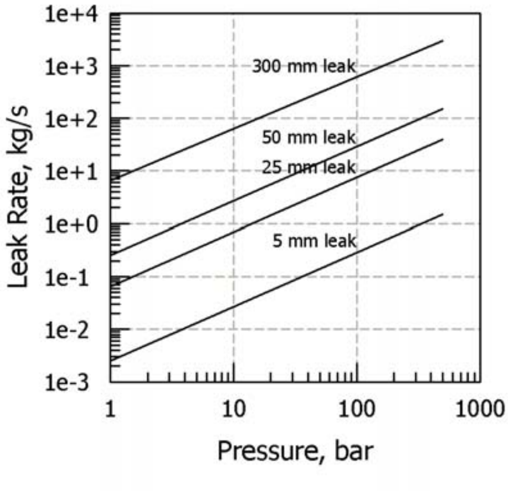


Figure C-2
Mass leak rate gas (density = 20 kg/m³)

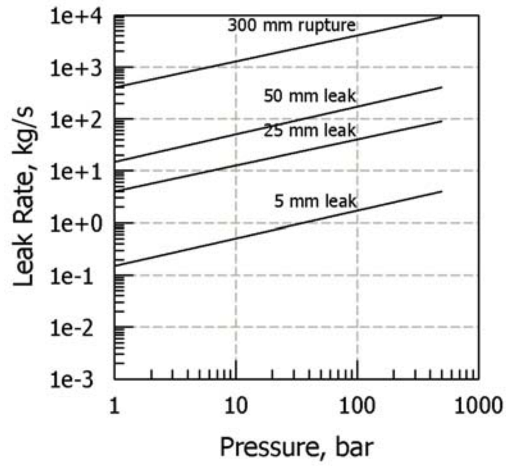


Figure C-3
Mass leak rate oil (density = 850 kg/m³)

C.1.5 Hole Size Correction

When the event sizes are defined by initial release rate and not hole size, then it will be necessary to determine the hole sizes which relate to the release rates in order to allocate these consequences. This will vary from segment to segment given that the pressures and fluids may vary.

An approximation of hole size given the release rate and pressure can be given as follows or, less precisely, from Figure C-2 and/or Figure C-3.

Gas release (approximation for methane):

$$d(m) = \sqrt{\frac{4QT_i}{\pi C_D P_i} 0.585 \sqrt{\frac{k}{R}}}$$

Where:

Q = Initial release rate in kg/sec.

T_i = Initial temperature of the segment (K)
C_D = Discharge coefficient, usually 0.85 for gases
P_i = Initial pressure of the segment (N/m^2)
k = Gas constant given by C_P/C_V = 1.3 for natural gas
R = Gas constant (8.314 J/K.mol)

Liquid release:

$$d(m) = \sqrt{\frac{4Q}{\pi C_D \sqrt{2\rho(P - P_a)}}}$$

Where:

Q = Initial release rate in kg/sec.
C_D = Discharge coefficient, usually 0.61 for liquids
ρ = Liquid density (kg/m^3)
P = Pressure of the segment (N/m^2)
P_a = Atmospheric pressure, 105 N/m^2

C.1.6 Ignition Probability Correction

The probability of ignition is a function of concentration of gas in a module, itself a function of leak rate and ventilation rate. It is, therefore, necessary that the differences in hole size be resolved before the same probability of ignition can be assumed. Should there be differences that lead to a correction of hole sizes, then the probabilities of ignition will also need to be corrected.

The probability of ignition is a function of the concentration of gas in relation to the lower explosive limit, and the number and type of ignition sources. Since using a different hole size will affect the calculated gas leak rate, then the probability of ignition will vary with mass leak rate, a function of hole area. Therefore, probability of ignition will vary with the square of the hole diameter.

Therefore, adjustment of the hole sizes between the QRA and RBI should have the ignition probabilities adjusted by the square of the differences in hole size, following:

$$P_{RBI}^{ign} = P_{QRA}^{ign} \frac{diameter_{QRA}^2}{diameter_{RBI}^2}$$

Where:

P^{ign} = Probability of ignition
$diameter$ = Leak hole diameter

C.2 Identification and Review of any Existing Relevant Analyses

C.2.1 Background

It is recommended to re-use any existing analyses. Examples of typical analyses that may contain relevant information that can be re-used in an RBI context are QRAs (Quantitative Risk Analysis), TRAs (Total Risk Analysis) and RAM analyses (Reliability, Availability and Maintainability). Re-use of QRAs is the most common case.

It is recommended that qualified personnel are involved in the process of identifying, reviewing and specifying any re-use of such material. If feasible, the people responsible for the development of the chosen material should preferably be involved.

In the case where a QRA or any such analysis is available, the results can be used in the RBI. However, the following comments must be made:

— If a QRA is available, the results may be used as input to the RBI CoF analysis. However, often the QRA is focused on safety consequences, which implies that the environmental and economic impact will still need to be considered separately.
— It must be noted that QRA analyses are usually based upon generic failure frequencies. RBI should not be based on these generic data, since the failure frequency should be specific to the degradation mechanisms of specific components. Therefore, these generic failure frequencies should be removed and replaced with the specific probability of failure calculated using this Recommended Practice (see Appendix A). Furthermore, the QRA may not apply the same hole size distribution as those used in the Recommended Practice, i.e. only the consequence assessment of the QRA should be maintained; the failure frequencies and hole size distribution should be replaced based on specific degradation mechanisms (see Appendix A).

C.2.2 Guidelines – QRA / Personnel CoF

The following guidelines are proposed for the use of existing QRAs in RBI analysis, and are applicable for personnel CoF only:

1) Identify the segment limits used in the QRA. This should be done in parallel/together with the first activity described in Section C.1.3.
2) Obtain the event trees for the relevant segments.
3) Determine the risk level arising from inspectable events.
4) Remove the generic failure rate component from the event tree. The QRA event tree will show a leak frequency as the initiating event. This is based on historical or other data, and should be removed. The end event frequencies should be divided by the leak frequency to get the end event frequencies given a leak. The PoF assessment is then used to estimate the leak probability for the final risk assessment.
5) Check whether the hole sizes used in the QRA are relevant to RBI. This implies that the RBI degradation mechanism assessments need to be available. If the QRA hole sizes are not readily available, these can be calculated by qualified risk/process personnel or by using the simplified methods outlined in Section C.1.5. If the QRA hole sizes are close to those required by the RBI degradation mechanism assessments, then the hole sizes need not be adjusted and the event tree may be used directly (with correction for leak frequency only). Otherwise,
    — either use the event tree as is (with correction for leak frequency only) by conservatively mapping hole sizes,
    — or correct also for probabilities of ignition based upon corrected hole sizes. Corrected probabilities of ignition need to be calculated by qualified risk/process personnel or by using the simplified method outlined in Section C.1.6.
6) Tabulate corrected personnel CoF per segment with respect to the four hole sizes (Table A-4).
7) Identify the part diameters present in the segment.
8) Assign CoF based on the hole size distribution for that degradation mechanism, taking care that a hole size in excess of the part diameter is not used.

C.2.3 Guidelines – QRA / Economic CoF

The following steps should be carried out to use existing QRA results in RBI covering economic consequence assessments:

1) From the safety risk assessment, determine which end events contribute to fire and explosion for each segment, materials and degradation combination.
2) Determine what changes need to be made to the probability of ignition based on hole size differences between QRA and DNV-RP-G101.
3) Determine from the QRA the end event probabilities for these events.

4) Determine the likely extent of damage to equipment and structure, using, for example, equipment count/value, rebuilding time and cost.

5) Multiply the end event probabilities by the cost of that end event, and sum up for the specific hole sizes for that segment, taking the values in the same distribution as the hole size distribution to give the final economic consequence for that segment & degradation mechanism.

C.3 Development and/or Implementation of Customized Methods/Techniques

C.3.1 Steps in Consequence of Failure Assessment

Generally, the following steps are required to determine the consequences:

- System description – define the system parameters of interest for the CoF assessment. Generally the "system" will consist of the topsides of an offshore installation, or part of it.
- Development of an event tree as necessary.
- Calculation of the consequences for all end-event tree outcomes.
- For all combinations of isolatable sections, modules, leak sizes[1]):
- Calculation/estimation of event tree branch probabilities.
- Calculation of the CoF contribution of all end-event tree outcomes.
- Sum all CoF contributions to calculate the weighed total expected consequences for safety, economics and environmental impact.

1) Some risk analysis may result in hundreds of event tree instances.

C.3.2 Development of an Event Trees

The calculation of the event tree probabilities is a complex matter. The probability of ignition, given that a leak occurs, is typically a function of the leak rate, concentration of flammable species, and the number of ignition sources within each module.

The method described in this appendix covers calculations of consequence of failure resulting from an ignited and an unignited leak in terms of safety, economic and environmental consequences.

Figure C-4, Figure C-5 and Table C-2 illustrate and explain an example of a simple event tree. More information and guidance on end events can be found in Sections C.3.3 and C.3.4.

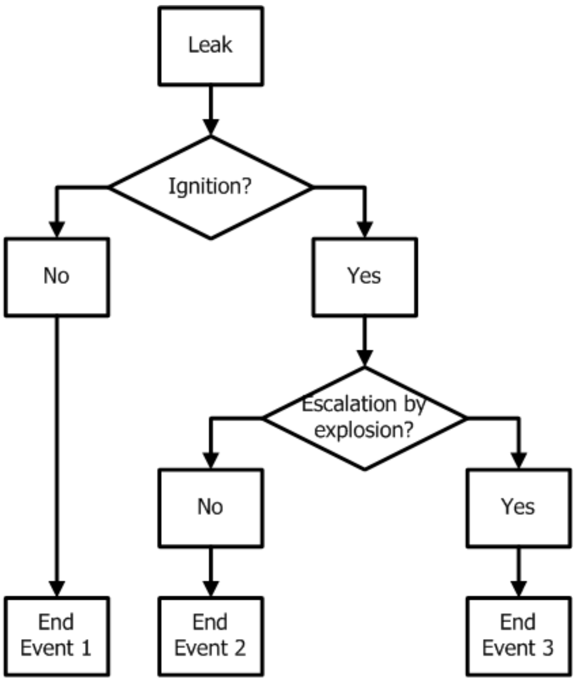
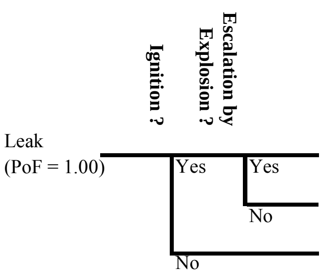


Figure C-4
Simple event tree



	Probability of Occurrence	CoF of End Events Safety	CoF of End Events Economics	CoF of End Events Environm.		Contribution CoF Safety	Contribution CoF Economics	Contribution CoF Environm.
End Event 3	P3	S3	B3	E3		P3 x S3	P3 x B3	P3 x E3
End Event 2	P2	S2	B2	E2		P2 x S2	P2 x B2	P2 x E2
End Event 1	P1	S1	B1	E1		P1 x S1	P1 x B1	P1 x E1
					Total CoF	(P1 x S1) + (P2 x S2) + (P3 x S3)	(P1 x B1) + (P2 x B2) + (P3 x B3)	(P1 x E1) + (P2 x E2) + (P3 x E3)

Figure C-5
CoF Calculation for simplified event tree: one event tree for each hole size

Table C-2 Description of end events for Figure C-4

End Event No.	*Description*	*Occurrence Probability*
1	There is a leak, but neither ignition nor explosion occurs.	$P_1 = (1 - P_{Ign})$
2	There is a leak, and the leaking gas is ignited. However, there is no explosion, only a fire.	$P_2 = P_{Ign} \times (1 - P_{Esc})$
3	There is a leak and the leaking gas is ignited. This is followed by an explosion, giving a blast overpressure that exceeds the design capacity of the blast wall, causing damage to the neighbouring module.	$P_3 = P_{Ign} \times P_{Esc}$

Where:

P_{Ign} = Probability of Ignition
P_{Esc} = Probability of Escalation

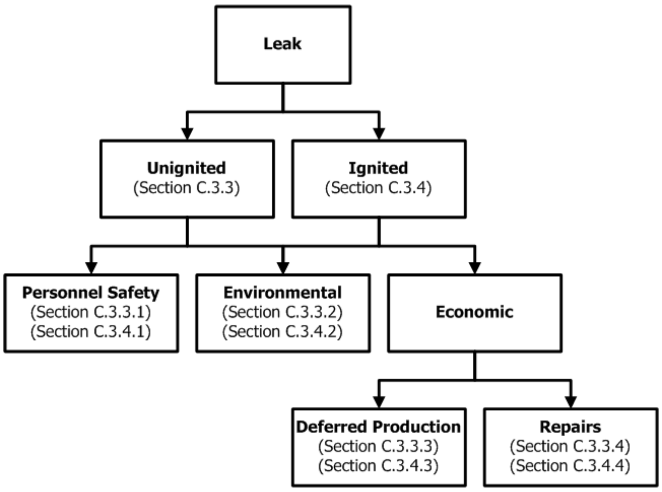


Figure C-6
Calculation of consequence of failure

C.3.3 Consequence for End-Event Tree Outcome – Unignited Leaks

Unignited consequences consider the effects of any toxic release on personnel, the economic costs of deferred production and repairs, and the environmental consequence of a liquid spill in the sea.

C.3.3.1 Personnel Safety Consequences

Generally pure toxic substances are not present in large quantities on offshore installations. The modelling is similar to that for gas and oil, and involves release rate calculation (can be estimated by using Figure C-2 and/or Figure C-3), dispersion (and hence the gas concentration), and consequence/impact assessment.

Note that nitrogen and carbon dioxide can have an asphyxiating effect since they replace the oxygen available in air. Hence, in high concentrations (generally in confined areas), these could cause fatal injury to personnel. The safety consequences are determined by the remaining concentration of oxygen in the air: a certain percentage of fatalities can be assumed in a module if the oxygen concentration reduces to less than a certain vol%.

Hydrogen sulphide is a highly toxic substance, but generally does not exist in pure form on an offshore installation. Hydrogen sulphide is mostly found as a component of a mixture predominantly of hydrocarbons. It is the major toxic gas encountered offshore and it has a greater explosive limit range than methane. The safety consequences for the non-ignited event are determined by the concentration of hydrogen sulphide and the exposure time. The fatality rate is normally calculated from a fluid specific probit relation, which requires the concentration of toxic gas in the confined area (in this case the module) and the exposure time as input. For carrying out simplified RBI assessments, it may be an advantage to work with a single value criterion, i.e. to relate the fatality fraction to the concentration only. A person exposed to a hydrogen sulphide vapour with a concentration between 500-1000 ppm (parts per million) will suffer from eye irritation, vomiting and possibly immediate acute poisoning [AIChE 1989]. LC50 values (i.e. concentration at which 50% of exposed population is killed) for 30 minutes' exposure are in the range of 450 to 1600 ppm, depending on which literature source is quoted.

C.3.3.2 Environmental Consequences

General

In considering environmental consequences, releases can be classified as oil (including condensate), gas or chemical. These are further discussed below.

Chemical releases are usually subject to legislative, or company imposed limits for releases into the environment. The consequences of exceeding these limits are typically case by case fines.

The measurement units for environmental consequences can be volume or mass released, or units of currency.

The use of mass or volume released facilitates calculation, as the contents, phase and volume of the ESD segment of the process are used elsewhere in consequence calculations.

Liquid Releases

In the case where environmental consequences are to be measured in volume of liquids lost to the sea, then it is necessary to estimate this figure for each relevant system and segment.

It will be necessary to determine the amount of liquid that will fall into the sea and not be contained within bunding or by plated decks and drains; this will depend strongly on the design of the installation as well as the position of the leaking part, the pressure within the system, the monitoring devices and the volume that can be lost.

A coarse approximation that can be used: assume that all liquid contained within a system or segment is released by a leak, resulting in a pool of the same volume of liquid as was contained within the system or segment. An estimation of the capacity of the drains to handle such a volume without overflowing to the sea can be made if the decking in the area is plated. Where the deck is made from grating, then the entire spilled volume can be assumed to fall through; if plated deck is beneath, then estimate the drains' capacity as previously.

Where the estimated volume of liquids reaching the sea is unacceptable, then a more detailed estimation can be made on the basis of expected leak size and location. This will couple the consequence estimation to the degradation mechanism for leak size and location, and can account for slower leak rates than that used in the coarse approximation.

The consequences of oil releases can be associated with political repercussions, a damaged reputation and clean-up costs. Environmental consequences from offshore topside oil leaks are considered to present only minor damage to global and local biotopes. Generally, the volume that can be released is limited to the contents of the equipment and even more so by the contents of an isolatable segment. Releases from pipelines, drilling activities and from storage vessels represent a significantly larger volume and are to be considered separately.

Direct costs related to oil releases are mainly related to the clean-up costs if the spill drifts towards shore. The actual effect will depend on the location of the field, oil type, oil drift conditions, temperature, evaporation, etc. For a given case, a fixed money value per tonne of oil released may be used.

The cost of clean-up for ship accidents may vary between US$ 700 to US$ 50 000 per tonne released, typically for accidents close to shore. Offshore platforms are usually located several miles offshore and, where no other basis is available, e.g. company goals; $10 000/ton is suggested as a conservative value for application in a coarse evaluation: i.e. the cost consequence for oil release, in monetary units per volume unit is given by:

$$C_{Environment} = V_{Release} \times (C_{Clean-up} + C_{Lost\ product})$$

Where:

$V_{Release}$ = Volume of oil released into the sea
$C_{Clean-up}$ = Cost of cleanup, monitory units per released volume units
$C_{Lost\ product}$ = Cost of oil that is lost in the release, monitory units per volume

Note that the $V_{Release}$ can be adjusted to account for specific factors on the installation, for example:

- The volume of oil released will be affected by the phases in the isolatable segment. For example, in two-phase system, the oil content will be less than total volume;
- Possible oil release resulting from systems such as produced water, oily water;
- Not all oil from a release may reach the sea: drains, flooring (open, closed), etc. may reduce the volume reaching the sea.

Gas Release

Gas releases to the atmosphere have received less attention than oil releases and are more typically controlled releases subject to taxation or concessions for flaring or venting. Accidental releases may be subject to fines issued on a case by case basis depending on specific circumstances.

Other Fluids/Chemicals

A number of chemicals are used offshore for inhibition, chemical treatment etc. that may be harmful to the environment. Chemical releases are usually subject to legislative, or company imposed limits for release of certain chemicals into the environment. The consequence of exceeding these limits is typically fines that are stipulated on a case by case basis depending on the circumstances.

C.3.3.3 Economic Consequences: Cost of Deferred Production

The value of deferred production is calculated as the value of production per hour multiplied by the number of hours at the reduced production rate. This can be expressed as a Net Present Value using a suitable discount rate, or as a fixed currency sum.

The amount of deferred production will depend strongly on the design of the installation process system(s) and their interaction. Production systems with several parallel trains can usually be operated with one train isolated so that the installation will be able to produce at a reduced rate until the damaged train is repaired and re-commissioned. The value of deferred production will therefore be less than for a single-train installation where any leak will require full production stop during the entire extent of repair.

The time-profile of deferred production for each part of the pressure-retaining systems is preferably defined so that it can be applied to all parts of that system or part-system.

The profile can typically include the time taken in repair and the individual process and well characteristics for restoring production from the stop or partial-production condition.

It is often necessary that a number of downtime profiles associated with deferred production are defined such that each part of the installation's systems that has an effect on production can be assigned a profile. These profiles describe the amount of production that can occur from the time a leak begins, until the completion of repairs and resumption of normal operations. The profiles can then be used as representative for the loss of production over time for individual equipment and piping.

The evaluations and estimates can be based on the PFDs and P&IDs for the installation. They involve reviewing the production process from well to export facilities, and determining what the effect on production would be if a leak arose in each section of piping and each piece of equipment, and developing the deferred production profiles on this basis.

Utilities systems are also typically included because in many cases their failure will cause failure of the process (e.g. water injection, instrument air, chemical injection) or require shutdown (e.g. unserviceable firewater).

The following steps can be applied:

1) Review the contents of the part. If hydrocarbon-containing, a leak is likely to give rise to an alarm and production shutdown. There may be a delay whilst the area is degassed and made safe. If the contents are non-hazardous, then there may not be a shutdown, but if there is, then there may be some time taken in finding and eliminating the leak.
2) If there are parallel trains that can be isolated from the leaking section then, after isolation, production may be able to recommence at a lower rate – depending on the capacity of the parallel trains.
3) The time taken to increase production from one level (e.g. from run-up, partial run-up) to another is individual to the installation and reservoir conditions, and is typically determined through consultation with the operations personnel for the installation.
4) Estimate the repair or replacement times that are likely, include availability of repair/replacement equipment, dimensions of the piping and equipment to be repaired, the service of the equipment (hazardous/non-hazardous), materials of construction, the size of the leak and the company maintenance and repair strategy.

C.3.3.4 Economic Consequences: Cost of Repairs

Similar to ignited end events, it will be necessary to judge the extent of damage within a module, and therefore the cost of repairs and replacement, as a result of the leak. Very often these are limited to the failing equipment/piping itself, or the equipment/piping in its direct vicinity. Generally these costs will be small compared to the cost of deferred production.

The cost of repairs in terms of deferred production is contained within the production loss profiles described in Section C.3.3.3, making sure that the specific repair methods are addressed where these will have an effect on the repair time. In addition, the costs of materials, man-time, mobilisation of personnel and equipment to the installation, provision of specialist services, cleaning of the work area, and similar, may be estimated in financial terms and added to the cost of deferred production.

C.3.4 Consequence for End-Event Tree Outcome – Ignited Leaks

Ignited consequences consider the effects of an ignited gas or liquid release on personnel, the cost of damage to the installation by fire and blast, the cost of deferred production and subsequent environmental consequences.

C.3.4.1 Personnel Safety Consequences

The safety consequences are calculated based on the average number of personnel present in the module that is impaired, either immediately (i.e. the leak occurs in this module) or delayed (i.e. due to escalation). In calculating the average number of fatalities, any difference in night and daytime population can be accounted for, as well as unusual operations requiring significant increases in personnel numbers (e.g. modification and operations simultaneously). As a conservative assumption, it can be conjectured that all personnel within the impaired module at the release moment are fatally injured.

C.3.4.2 Environmental Consequences

In the case of ignited leaks, it is not expected that significant volumes of liquids will be deposited in the sea during the fire. However, the condition of the installation following an explosion or a severe fire may be such that wells or storage tanks will leak.

In addition, the large amount of smoke generated by such fires may be a concern. As yet, there are no risk acceptance limits developed or calculation methods for estimating the consequence; this will have to be treated qualitatively. Financial penalties may be applicable in certain cases.

Further, there may be a political element to the environmental consequence once there has been press exposure. Consideration can also be given to loss of reputation and loss of share value.

C.3.4.3 Economic Consequences: Cost of Deferred Production

It is likely that production will not be possible whilst repairs take place. The downtime can be based on judgement. The cost of the lost or deferred production is derived as product of downtime and deferred production.

Production loss related to major damage caused by ignited events is determined by the reconstruction and repair time, which is plant/project specific. It is largely determined by long-lead items such as compressors, pressure vessels and heat exchangers made of special materials.

For ignited cases, the downtime can be related to the amount of damage sustained, if no other data is available. A relationship derived from the “Dow Fire and Explosion Index” [AIChE 1994] is considered to give a reasonable correlation between property damage and repair/outage time.

C.3.4.4 Economic Consequences: Cost of Repairs

When estimating the damage costs (cost of repairs and replacement, as a result of a fire or explosion), it is necessary to judge the extent of damage. Damage to the installation may be confined to a single module, or if the fire or blast is of sufficient magnitude, additional modules or the whole installation may be damaged or lost.

— In the case of a jet fire, it is expected that any items within the radius of the fire may be damaged or destroyed.
— In the case of a pool fire, all equipment that stands within the pool can be considered damaged or destroyed.
— Where equipment subject to fire loading also contains significant amounts of hydrocarbons, the effects of the fire loading and duration can be used to estimate knock-on effects. In these cases, passive and active fire protection can be considered as mitigating factors.
— The blow-down capability, i.e. reducing pressure and volume of fluid available to fuel the fire, may be considered for both the leaking equipment and other equipment subject to fire loading; the effects of the fire can be adjusted accordingly.
— Further mitigating factors, such as fire and gas detection, deluge and sprinklers, together with the philosophy for their use (e.g. deluge start on confirmed gas detection and before fire detection), can be taken into account.

The costs can be taken from the project new-building data corrected for inflation and net present value, or it can be estimated on the basis of general industry knowledge. It typically includes repairs and replacement of structural, electrical, HVAC, control, piping, equipment (pumps, compressors etc.). Note that the cost of deferred production is not included in the repair cost.

C.4 Consequence of Failure Assessment Methods

C.4.1 Introduction

In the case where existing analyses are not available or are judged inappropriate to use in the RBI context, then the consequence of failure can be further assessed either in a qualitative, quantitative or semi-quantitative manner. These assessments methods are described in this section.

C.4.2 Quantitative Assessment Methods

Groups of equipment that have been defined can be further assessed by using quantitative methods.

For unignited leaks, quantitative methods for assessing the consequences of failures can be customized based on the guidelines and descriptions given in Appendix C.3.3.

For ignited leaks, it is recommended to use existing assessments, for example as described in Section C.3.4. If quantitative methods are developed for ignited leaks, these should be properly qualified, preferably by a third party.

C.4.3 Qualitative Assessment Methods

When applying qualitative engineering-judgement methods, it is recommended to carry out assessments by work-sessions as described in Appendix E. It is recommended that the degradation assessment results are readily available. A customized assessment form should be developed, taking care to include a checklist with all relevant parameters and leaving enough space to document the decision processes and discussions.

Examples of qualitative ranking scales which can be used for the consequence of failure are shown in Section 4 of this RP’s main body.

It shall always be assumed that a leak has occurred according to the configuration given by the degradation mechanism assessment.

It is important to keep a conservative mindset and also cross check with and qualitatively “calibrate” against any existing quantitative assessments in order to avoid unreasonable results.

C.4.4 Semi-Q Assessment Methods

The customized assessment form can be further developed with simple rules that can be used to assign CoF categories in a “semi-qualitative” / “semi-quantitative” manner. If such a method is developed and implemented, a work session as described above should also be part of the implementation for the sake of quality verification. An example of a starting point for a semi-quantitative method is outlined below.

Example of Semi-Q method

A sketch for a simple semi-quantitative / semi-qualitative method for CoF evaluation is suggested in the following. It is based on combining information about fluid category and area classification (with regard to levels of hazard).

Step 1 Classify areas on the installation. Table C-3 below is a suggested starting point for classification of areas on the installation. Should a QRA be available (or other recognized sources of similar information), a more detailed sub-classification should be possible to establish if considered beneficial to the planning process.

Step 2 Based on the area classification and Table C-4 to Table C-6, the next step in the process is to consider the specific product service codes and allocate CoF categories (not ranges) based on installation-specific knowledge. This should be done in the form of (a) work session(s). This installation-specific knowledge would have been documented during the process of system review, description and modelling (see Section C.1.3). Any decision made to go beyond the ranges suggested in Table C-6 should be documented and verified by a third party (external consultant or expertise from other parts of the organisation).

Table C-3 Classification of areas

*Area class (AC)**	*Description*
AC0	Hazardous area – QRA has not been carried out as a part of design/engineering/modification.
AC1	Hazardous area – QRA carried out/utilized during design/engineering/modifications. QRA based on recognized methods and preferably carried out by recognized risk management team/company.
AC2	Non-Hazardous area.

* More detailed sub-classifications can be established; for example AC1.1, AC1.2, etc.

Table C-4 CoF categories

Category		*Description*
(A)	Insignificant	A leak implies insignificant likelihood of human injury, and insignificant environmental and economic consequences.
(B)	Minimal	A leak implies minimal likelihood of human injury and minimal environmental and economic consequences.
(C)	Low/Small/ Minor	A leak implies small likelihood of human injury, minor environmental and economic consequences.
(D)	Normal/ Medium	A leak implies likelihood of human injury, significant environmental pollution or significant economic or political consequences.
(E)	High	A leak implies high likelihood of human injury, massive environmental pollution or very high economic or political consequences.

Table C-5 Fluid categories

Fluid Category	*Description*
I	— Typical non-flammable water-based fluids. — Non-flammable substances which are non-toxic gases at ambient temperature and atmospheric pressure conditions. Typical examples would be nitrogen, carbon dioxide, argon and air.
II	— Flammable and/or toxic substances which are liquids at ambient temperature and atmospheric pressure conditions. Typical examples would be oil petroleum products. Methanol is an example of a flammable and toxic fluid. — Non-toxic, single-phase natural gas. — Flammable and/or toxic fluids which are gases at ambient temperature and atmospheric pressure conditions and which are conveyed as gases and/or liquids. Typical examples would be hydrogen, natural gas (not otherwise covered under category D), ethane, ethylene, liquefied petroleum gas (such as propane and butane), natural gas liquids, ammonia, and chlorine.

Table C-6 Fluid categories, area classes (AC) and CoF

Fluid Category	*Location Class / CoF Category*		
	AC 0	*AC 1*	*AC2*
I	D(E)*	B-D(E)*	A-D(E)*
II	E	C-E	C-E

* Some systems may have such an essential function that the CoF can be "high".

C.5 Transfer of Results to Chosen Equipment Level of Detail

Once consequences have been evaluated at assessment/equipment Levels 1 and 2 (system level and ESD-segment level), the results can be transferred to a lower equipment level. Transferring results to a lower level involves:

— Linking tags and parts to the groups that have been defined and evaluated in the previous activities. This work can be time-consuming and error prone as it is often done manually. It is recommended to mark up drawings (P&IDs) and break down the work into manageable packages.
— Adjusting the consequence assessments with regard to potential hole sizes and the size of the tags and parts of the lower level.

APPENDIX D
RISK ACCEPTANCE

D.1 Risk Acceptance Limit – Concept

The role of inspection is to confirm whether degradation is occurring, to measure the progress of that degradation, and to help ensure that integrity can be maintained. The decision process regarding when to inspect can be done in a quantitative, qualitative or semi-Q manner and should be carried out separately for each type of risk to be assessed.

The goal of maintenance/inspection program is to contribute in maximizing availability and profit without compromising safety (personnel and environment). The risk acceptance limit for planning inspection should therefore be based on using authority and corporate/management targets related to availability, profit and safety. Risk acceptance limits for inspection planning derived from such targets must not be confused with pure technical/engineering acceptance criteria such as acceptable wall thickness derived from various engineering codes. Cross checking with relevant codes is nonetheless recommended when developing inspection plans. Furthermore, when inspection results are available, integrity may be evaluated based on such relevant engineering or fitness-for-purpose codes.

D.2 Using the Risk Limit Concept – Challenges/ Important Issues

Utilizing the risk limit concept to plan inspection for all the static process equipment of an offshore installation presents several challenges. The most important ones are the following:

- To be able to manage installation risk so that it lies below the limits acceptable to the operator; the risk acceptance limits for each type of risk should be defined.
- As there are several risk acceptance limits, it is necessary to have a decision logic regarding the order of importance of these limits in deciding which limit is to govern the time to inspection. This order of importance should be recorded.
- It is not practical to work according to this concept directly at a component level. It will be necessary to make some simplifications by generalising, averaging and/or transferring information from a higher level down to such a component level.
- Authority and corporate/management targets related to availability, profit and safety usually have a scope which is beyond the issues covered by inspection. A method for deciding an "appropriate" fraction of these targets needs to be developed.

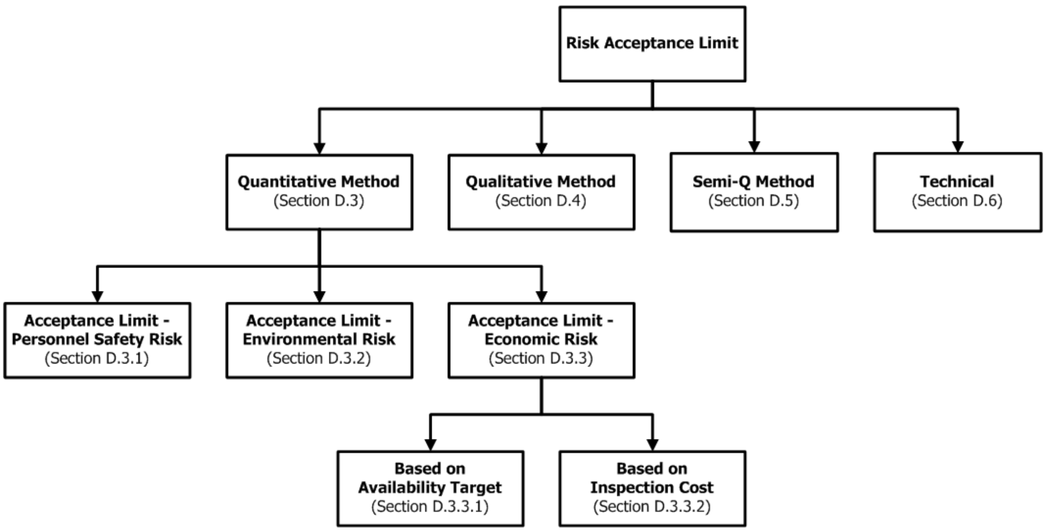


Figure D-1
Methods for determining the risk acceptance limit

D.3 Risk Acceptance Limit - Quantitative Method

When applying quantitative methods, risk acceptance limits should be established for each type of risk. These limits are used to prioritize items for inspection, and derive the timing of inspection such that inspection is carried out prior to the risk acceptance limit being breached. This would allow either the reassessment of the risk level based upon better information, detailed evaluation of any damage, or the timely repair or replacement of the degraded component. The derived inspection timing is calculated based on the specific characteristics of the plant and components being analysed. An example is when quantitative safety limits set by authorities are used to derive a specific risk acceptance limit for a specific plant based on how the inspectable items of the plant contribute to the total risk. The risk calculated for these particular items can be compared to the authority-based risk acceptance limits in order to time their inspection.

D.3.1 Acceptance Limit – Personnel Safety Risk

When it comes to the risk acceptance limit related to safety, it is common practice in some regions of the world to have safety limits set by authorities. Operators need to carry out quantitative risk analyses in order to determine whether or not the safety levels on their plants are acceptable compared to the authorities' limits. In such cases and with the help of some statistics, it is possible to derive a risk acceptance limit based on the following:

- The quantitative risk analyses usually present how process accidents are estimated to contribute to the total risk (typically 30-50% contribution).
- Statistics regarding contribution of process accidents from different types of equipment (about 30% of process accidents occur in piping).
- Statistics regarding "inspectable" events. Historic data shows that corrosion causes about 30% of piping failures in the process system.

The idea is to use this type of information to derive an acceptance limit which represents a fair share of the total risk acceptance limit set by the authorities. The derived limit needs to be again divided among the components that are being planned for. It is recommended to divide the derived limit by the number of ESD-segments or corrosion groups in the process system (Level 2 in the equipment hierarchy presented in Section 5.3).

D.3.2 Acceptance Limit – Environmental Risk

The measurement units for calculated environmental consequences can be volume or mass released, or units of currency based on volume or mass and clean-up costs. The use of mass or volume released facilitates calculation, as the contents, phase and volume of the ESD segment of the process are used elsewhere in consequence calculations. If clean-up costs and fines are considered when calculating the economic consequences and risks, then the environmental assessment is covered by the economic assessment. This approach is recommended if a quantitative method is chosen to be used. If the environmental risk assessment is kept separate from the economic risk assessment, it is recommended to use qualitative methods.

D.3.3 Acceptance Limit – Economic Risk

D.3.3.1 Based on Availability Targets

A method similar to the one used for safety acceptance limits can be used for economic risk. Information on availability targets can be broken down in the same way and used as a risk limit for planning inspection.

D.3.3.2 Based on Inspection Cost

When the degradation mechanism is well understood, it is possible to use an approach where inspection is carried out only when it is “worth spending the money”. In other words, inspection is cost-effective when the economic risk and the cost of inspection are in the same order of magnitude. When it comes to the cost of inspection, it is not practical to give individual estimates of the inspection cost related to every one of the relevant parts. Average values should be used to begin with, and if necessary, uncertainties can be included. At later stages of the analysis, it might become relevant to look at individual components in more detail.

D.3.4 Recommended Application of Quantitative Methods

When applying quantitative methods, it is recommended to give the safety limit first priority. The economic risk limit based on inspection costs can then be used to decide on how long inspection can wait. In other words combining these two limits gives a cost-effective inspection plan without compromising safety.

For the parts of the process where safety is not an issue, the economic risk limit based on availability targets should be used together with the economic risk limit based on inspection cost. In other words, combining these two limits gives a cost-effective inspection plan without compromising availability targets.

D.4 Risk Acceptance Limit – Qualitative Method

When qualitative or semi-quantitative methods are being used, a decision matrix should be applied. This decision matrix will typically be a generic, company specific matrix which is likely to be conservative. An example of such a matrix is shown in Figure D-2 where the inspection interval is given by the numbers in the cells. It is recommended that such inspection intervals be dynamic intervals subject to change based on qualified assessments of inspection results.

Application of qualitative methods for acceptance limits and inspection times requires highly experienced personnel, both from a general point of view and from a plant specific point of view. The principles described for quantitative methods apply for qualitative methods also. Any judgement leading to an inspection plan should take into account many of the same matters considered when carrying out quantitative calculations.

One or several decision matrices covering the different risk types should be developed for both rate models, susceptibility models and any other types of models being considered.

D.5 Risk Acceptance Limit – Semi-Quantitative Method

The following is suggested as a starting point for topside applications. If it is feasible, the acceptable probabilities of failure should be adjusted/calibrated against the ones used on any of the operator’s identical or similar installations that are known to have adequate inspection management systems.

Guidance note:

— A leak in the main hydrocarbon system is a condition that can compromise the integrity of the installation.
— A leak in the utility system is a condition that renders the topside installation unsuitable for normal operations. The acceptable PoF limit is therefore chosen to be less conservative than for HC systems.
— The values are based on project experience and engineering judgement.
— It is assumed that the CoF is assessed semi-quantitatively according to example given in Appendix C.4.4. Consequence categories are according to Figure D-2. The PoF assessment is assumed to have been carried out quantitatively or semi-quantitatively resulting in numerical values to the PoF.
— See Appendix F for inspection timing.

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PoF Ranking	PoF Description	Time to Inspect (years)				
5	(1) In a small population, one or more failures can be expected annually. (2) Failure has occurred several times a year in the location.	Corrective Maintenance	4	2	1	1
4	(1) In a large population, one or more failures can be expected annually. (2) Failure has occurred several times a year in operating company.	Corrective Maintenance	4	2	1	1
3	(1) Several failures may occur during the life of the installation for a system comprising a small number of components. (2) Failure has occurred in the operating company.	Corrective Maintenance	Corrective Maintenance	4	2	2
2	(1) Several failures may occur during the life of the installation for a system comprising a large number of components. (2) Failure has occurred in industry.	Corrective Maintenance	Corrective Maintenance	8	4	4
1	(1) Several failures may occur during the life of the installation for a system comprising a large number of components. (2) Failure has occurred in industry.	Corrective Maintenance	Corrective Maintenance	8	8	8
CoF Types	Safety	No Injury	Minor Injury Absence < 2 days	Major Injury Absence > 2 days	Single Fatality	Multiple Fatalities
	Envirnoment	No pollution	Minor local effect. Can be cleaned up easily.	Significant local effect. Will take more than 1 man week to remove.	Pollution has significant effect upon the surrounding ecosystem (e.g. population of birds or fish).	Pollution that can cause massive and irreparable damage to ecosystem.
	Business	No downtime or asset damage	< € 10.000 damage or downtime < one shift	< € 100.000 damage or downtime < 4 shifts	< € 1.000.000 damage or downtime < one month	< € 10.000.000 damage or downtime one year
CoF Ranking		A	B	C	D	E

Figure D-2
Example of decision risk matrix

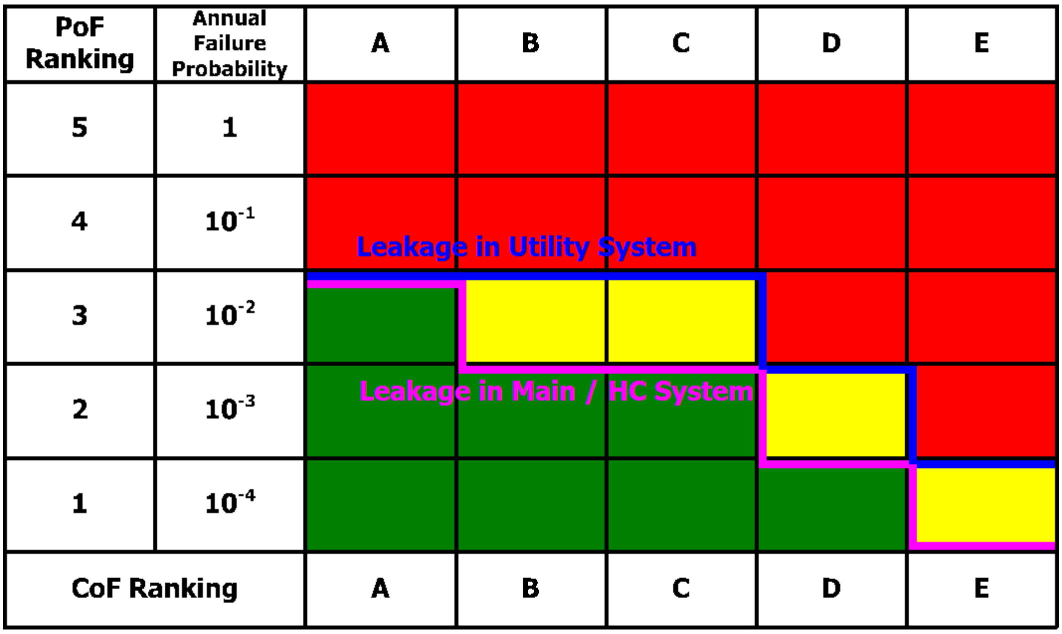

Figure D-3
Probability of Failure acceptance limit (PoF_{Limit}) versus CoF category

Table D-1 Probability of Failure acceptance limit (PoF_{Limit}) versus CoF category

Leakage type	*Consequence category*				
	A	*B*	*C*	*D*	*E*
Leakage in utility system	10^{-2}	10^{-2}	10^{-2}	10^{-3}	10^{-4}
Leakage in main/HC system	10^{-2}	10^{-3}	10^{-3}	10^{-4}	10^{-5}

D.6 Risk Acceptance Limit – Technical Criteria

D.6.1 Probability of Failure Acceptance Limit

To allow the time-to-inspection to be calculated, it is recommended that the risk acceptance limit is converted to a probability of failure acceptance limit (PoF_{Limit}). This can be done using the Figure D-3 and Table D-1. Depending upon the consequence of failure category, the corresponding probability of failure limit can be read. This limit should be expressed for each type of risk considered. Note that the same part may have more than one probability of failure limit, depending on the consequence type.

D.6.2 Time to Inspection – Simplified Method for Different Degradation Models

D.6.2.1 Rate model

The method presented in this section facilitates the calculation of the time at which the PoF will equal the probability of failure acceptance limit (PoF_{Limit}). This is also the latest time at which inspection should be carried out to check that risk acceptance limit is not exceeded.

The calculation is based on the given wall (t_0) thickness, wall thickness at which a release is expected ($t_{release}$), mean damage rate (d_{mean}) and a confidence factor (a) to account for the uncertainty in the rate of corrosion.

The time at which ($PoF = PoF_{Limit}$) is given by:

$$\text{Time to PoF}_{\text{Limit}} = a\frac{t_0 - t_{release}}{d_{mean}}$$

Where:

t_0 = Current wall thickness (mm).
This can be determined by inspection.

$t_{release}$ = Wall thickness at which a release is expected (mm). This can be derived from first principles, or from appropriate codes or formula such as ANSI/ASME B31.3 ANSI/ASME B31.G, BS 5500, ASME VIII, and DNV-RP-F101, using relevant operational loads.

d_{mean} = Mean damage rate (mm/year).
This is determined using measured values, expert judgement, or the guidance in Appendix A

a = Confidence factor.

The process steps are:

1) Determine the current wall thickness by inspection.
2) Determine the wall thickness at which a release is expected.
   a) Due consideration should be given to the degradation morphology: code formulae generally assume a uniform wall thinning, although some include defect size assessment. For localised damage that does not affect the wall stresses, it may be acceptable to set the release wall thickness close to, or as, zero; i.e. the release due to uniform wall loss will occur at thicker wall than local wall loss.
   b) It may be desirable to include other wall thickness criteria in the inspection plan, e.g. to check compliance with authorities' requirements. If other failure criteria are defined, such as consumption of corrosion allowance, the purpose of the evaluation should be considered and the consequences adjusted to suit, e.g. cost of remedial action, rather than a release.
   c) Some code formulae include optional explicit safety factors: it is suggested that these are removed for the purpose of RBI as margins are implicitly included in the calculations and vary with risk.
   d) The code formulae give wall thickness requirements for pressure retaining purposes. Other loads should also be considered and a thicker limit should be stipulated if the code suggests an impractically thin wall for general thinning.
3) Determine the mean rate of corrosion (d_{mean}) from measured values, expert judgement, or using the guidance in Appendix A.
4) Determine the confidence factor (a) using the procedure given below.
   a) This simplified method uses pre-defined distributions, as referenced in Appendix A, and assumes that the mean damage rate is the only uncertainty variable.
   b) Determine the maximum acceptable probability of failure for the item using the consequence of failure for that item and the type of risk (Section D.5).
   c) For mechanisms other then CO_2 corrosion:
      The confidence curves are given for three coefficients of variance (CoV) of corrosion rate only: 2.0, 1.0 and 0.33, representing high, medium and low spread respectively. A rough guide to decide the applicable CoV is given in Table D-2.
      Select the curve in Figure D-2 that is appropriate to the degradation mechanism, including a CoV. The curves in Figure D-2 apply to normal or log-normal distributions.
   d) For CO_2 corrosion:
      The confidence curve for CO_2 corrosion (Figure D-2) is given for two cases: uniform corrosion and local corrosion. These curves include the relevant CoV value. Depending upon the inspection results the correct curve can be selected.
   e) Use the selected curve, take the *Probability of Failure Limit* (PoF_{Limit}) on the horizontal axis and read off the corresponding *Confidence Factor* (a) on the other axis.
5) Calculate the value of (Time to PoF_{Limit}) using the equation:

$$\text{Time to PoF}_{\text{Limit}} = a\frac{t_0 - t_{release}}{d_{mean}}$$

6) Determine the time to inspection. The inspection should be scheduled to occur no later than the (Time to PoF_{Limit}). It may be preferred to calculate the (Time to PoF_{Limit}) for each risk type for the component of interest with the inspection scheduled for the earliest result.

Table D-2 Definition of confidence levels	
Confidence Level	*Description*
High (Confidence CoV ≈ 0.33)	— Service conditions are well known and do not fluctuate appreciably. — Inspection results show a consistent trend, with a high correlation coefficient when plotted against time. — A highly efficient inspection method is used and the measured results are validated. — Degradation models are derived from many data sources showing results that are generally consistent; where probabilistic models are given, the standard deviation is low.
Medium (Confidence CoV ≈ 1.0)	— Service conditions are well known and fluctuations are of a moderate nature. — Inspection results show a consistent trend, with some scatter and a reasonable correlation coefficient when plotted. — A normally efficient inspection method is used and the measured results are validated. — Degradation models are derived from only a small number of data sources showing results that are generally consistent; where probabilistic models are given, the standard deviation is moderate.
Low (Confidence CoV ≈ 2.0)	— Service conditions are not well known or have a considerable variation in pressures, temperatures or concentration of corrosive substances. — There are no inspection results, or if they exist then they show only a general trend, with extensive scatter and a low correlation coefficient when plotted. — A fairly efficient inspection method is used and the measured results are validated. — Degradation models are derived from one data source only; where probabilistic models are given, the standard deviation is high.

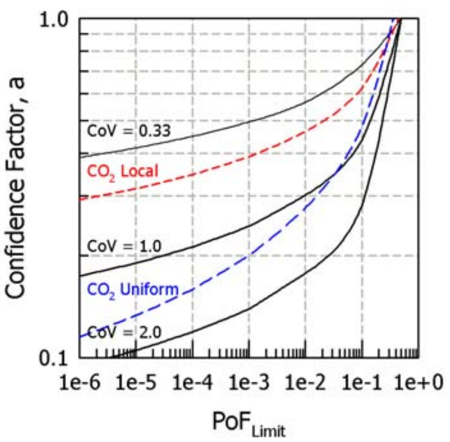

Figure D-4
Scale factor as a function of PoF_{Limit}

D.6.2.2 Susceptibility model

For a description of susceptibility models, see Appendix A. If any of the acceptance limits is exceeded then immediate action must be taken. This action may be one or a combination of:

— more detailed analysis
— assessment and repair of any damage
— change or treatment of the content so that it is less damaging
— reduction of operating temperature
— exclusion of damaging environment (e.g. coating, lining, exclusion of water from insulation)
— change of material type.

As previously mentioned, the onset and development of damage are not readily amenable to inspection. This means that the economical acceptance limit should take other things than inspection costs into consideration.

APPENDIX E
SCREENING

E.1 Introduction

It is recommended that the risk-based screening process is carried out as a working session amongst suitably qualified personnel, including staff with specific knowledge of the asset in question. The following type of personnel should be involved (also see Section 5.5): materials/corrosion; inspection; process/production; safety.

It is recommended that the materials degradation and damage evaluation sheets, included with this appendix, are used during the screening process to help guide discussion.

E.2 Probability of Failure

E.2.1 Introduction

Consider whether there is any possibility of failure, under the known operating conditions and taking into account the approximate chemical composition, the temperatures of the fluids and the effects of time. The boundary between low and high probability of failure has been set to approximately 10^{-5} per year, i.e. no significant degradation is expected with PoF of 10^{-5} or less.

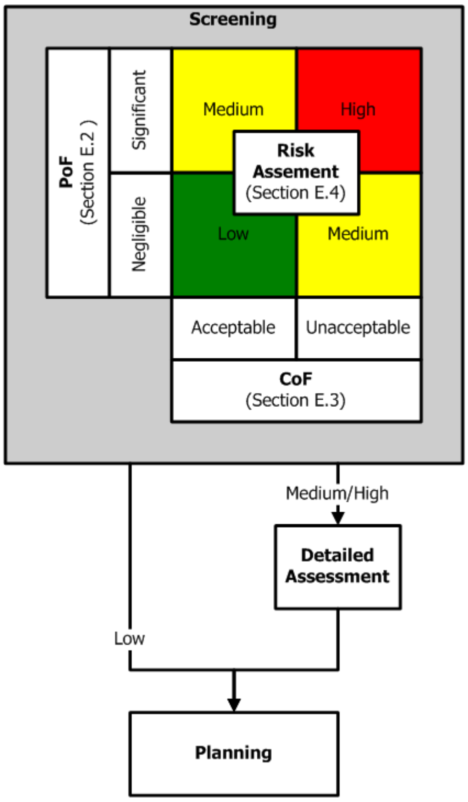

Figure E-1
Screening assessment for RBI process

It is not the intention to carry out a detailed evaluation, but to assess whether these conditions are likely to give rise to negligible degradation (“low”) or degradation rates that are not negligible (“high”).

Care should be taken to ensure that the consideration of process conditions accounts for future variations as the reservoir becomes depleted, such as increase in water cut, temperatures, or H_2S evolution. It is important also to account for likely excursions in process parameters due to upset conditions.

Consider the following for present time, their change with time, and what might happen in upset or start-up conditions. Consider also historic events, including testing during construction and commissioning, as well as past service. Do NOT include consideration of consequence in the probability! Any other causes of failure can be included in the assessment. This can include any known or suspected abnormal conditions that can cause concern.

Guidance note:

- Data requirements and screening guidance for probability of failure are given in Appendix A which treats each degradation mechanism.
- Appendix A should be consulted for the applicable mechanism.
- Care should be taken when using the appendix for guidance on probability of failure to ensure that the assumptions made regarding the conditions under which the components operate are applicable to the systems in question.

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E.2.2 External Degradation

Consider the probability of failure for each material that might arise as a result of the external environment, taking account of temperatures, coatings, the presence of water-retaining insulation and the effects of time.

Prompt questions:

- Coating: is there a coating, what type is it, what is its quality, how long does it take to degrade significantly?
- Insulation: is there insulation, does it retain water, is there heat tracing (temperature effect on both internal and external degradation)?
- Is there any data that indicates current condition – inspection reports, for example?

E.2.3 Internal Degradation

Consider the probability of failure due to combinations of materials, fluids, gases, temperatures and pressures, also including degradation due to erosion and the passage of chemicals within the systems. Consider also likely changes in the use of the system – such as use of water injection pipework for oil production.

Prompt questions:

- Consider possible degradation mechanisms arising from materials’ and fluids’ combinations. What about CRA or polymeric linings? Internal corrosion protection systems? Internal anodes?
- What are the effects of temperatures and pressures, also partial pressures? Note these may change through the system, and metal temperatures can be affected by heat tracing.
- Consider excursions in all process parameters.
- Consider sand production rates, proppant production, acid production.
- Consider water breakthrough over time.
- Consider increases in CO_2 with time if there is gas reinjection.
- Is there any data that indicates current condition – inspection reports, for example?

E.2.4 Fatigue

The probability of failure due to fatigue can be considered. Areas where there are known or suspected problems should be evaluated, for example small diameter side-branches of stainless steel. The significance of vibration sources should also be considered, such as poor or damaged support systems, reciprocating equipment, unbalanced rotating equipment and fluid hammer.

Prompt questions:

— Are there areas where vibrations are expected, or have been observed?
— Have any failures occurred?

E.3 Consequence of Failure

E.3.1 Introduction

Consider the following points for assessing the consequences of failure. The worst case scenario regarding leak is usually the best case to consider – do NOT include consideration of probability of failure in the consequence! If required, other consequences (besides safety, economic, environmental) can be assessed, such as the political consequence (in terms of adverse press coverage or loss of share value) that could arise from a spill or fire. The definitions of these other consequences must be discussed during agreement of the acceptance limits.

E.3.2 Personnel Safety Consequence

Acceptance criteria at a tag level are not always intuitively assessable in the screening session: experience shows that the boundary between "low" and "high" safety consequence can be taken as the possibility of personnel exposure leading to injury and a lost-time incident. Typically the loss of any flammable or toxic fluid or gas would be expected to give a "high" safety consequence.

Prompt questions:

— What is the effect of a leak?
— Is the fluid poisonous?
— Will there be ignition and/or explosion that might affect personnel?
— What is the likely population around any part of the system that might leak – might there be deaths or injuries?

Guidance note:

- A release of a fluid that is normally accepted as being difficult to ignite, such as diesel fuel, can still result in ignition due to impingement on hot surfaces.
- High pressure leak may result in formation of a mist that can readily ignite in the presence of equipment or work that may generate sparks.

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E.3.3 Economic Consequence (Deferred Production, Repairs)

A production shutdown would normally be expected to give a "high" economic consequence. However, due consideration must be given to the installation operational economics, such as field production profile, system redundancies and penalties that might arise from contractual production guarantees. The release into the sea of any hydrocarbon liquid or process chemical (unless specifically known to be benign, or of low volume) would be expected to give a "high" environmental consequence. Releases of gases into the air should be considered in the light of local regulations.

Prompt questions:

— What is the likely reaction to the detection of a leak? Will the platform shut down production, or partially shut down?
— Will there be damage to the installation, by fire and/or explosion, or acid attack, resulting in replacement costs and lost production?
— Are there clean-up costs associated with the leak?

E.4 Risk Assessment

After assignment of the probabilities and consequences, the system or vessel is assigned to detailed RBI or to maintenance activities as shown in Figure E-2. The most severe result for any of the consequence categories, taken with the most severe result for the probability categories, is used to stipulate the final outcome.

It is essential to assess whether the piping and vessels within a system experience different conditions, such as the possibility of water condensation within a vessel but not in the piping systems, and the effect of flow rates in piping and vessels on sand erosion.

The recommendations for action, as shown in Figure E-2, are developed on the basis that inspection is only effective in reducing the probability of failure. There may be other causes of failure with significant consequences that have not been considered because they are not within the scope of inspection.

The results of the screening process are that systems, groups or equipment items are assessed as having either "high", "medium" or "low" risk:

— Items with medium and high risk should be evaluated further (ref. Section 5.9).
— Items with low risk should be considered for maintenance activity as noted in Figure E-2.
— High consequence items should also undergo checks for degradation mechanisms not considered in the screening.

E.5 Revision of Screening

The screening process should be periodically revised as part of the overall inspection management process to ensure that the assumptions used in the evaluations remain valid. Changes in process or other conditions may result in systems or equipment moving to high risk and therefore should be subject to more detailed RBI assessments.

E.6 RBI Screening Briefing

The following are prompt questions to aid thought and discussions. These are by no means exhaustive:

— A combination of "High" probability and "High" consequence necessitates a detailed RBI analysis.
— A score of "Low" for either is a recommendation for maintenance activity.
— A scope of "Low" for both is a recommendation for "No Further Action".

Note:

Note: if the assessment leaves any cause for doubt, or information is lacking, a "High" rating should be assigned and further assessment carried out.

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<table>
<tr><td colspan="3">Probability of Failure</td><td colspan="5">Risk Categories and Screening Actions</td></tr>
<tr><td>5</td><td rowspan="4">$>10^{-5}$</td><td rowspan="4">Significant probability of failure</td><td rowspan="4">MEDIUM RISK
Inspection can be used to reduce the risk, but is unlikely to be cost-effective; the cheapest solution is often to carry out corrective maintenance upon failure.</td><td rowspan="4" colspan="4">HIGH RISK
Detailed analysis of both consequence and probability of failure.</td></tr>
<tr><td>4</td></tr>
<tr><td>3</td></tr>
<tr><td>2</td></tr>
<tr><td>1</td><td>$>10^{-5}$</td><td>Negligible probability of failure</td><td>LOW RISK
Minimum surveillance, with corrective maintenance, if any. Check that assumptions used in the damage assessment remain valid, e.g. due to changes in operating conditions.</td><td colspan="4">MEDIUM RISK
Consequence is high so actions (such as preventative maintenance) should be considered to ensure continued low probability as small changes in conditions can increase PoF and give high risk.</td></tr>
<tr><td colspan="3" rowspan="2">Consequence of Failure</td><td>Acceptable consequence of failure</td><td colspan="4">Unacceptable consequence of failure</td></tr>
<tr><td>A</td><td>B</td><td>C</td><td>D</td><td>E</td></tr>
</table>

Figure E-2
Risk matrix for screening

E.7 RBI Screening Form

<table>
<tr><td colspan="4">Installation:</td><td colspan="2">Rev:</td></tr>
<tr><td colspan="4">System No:</td><td colspan="2">Description:</td></tr>
<tr><td colspan="6">Function & boundaries:</td></tr>
<tr><td colspan="6">Dependent systems:</td></tr>
<tr><td colspan="6">Process & Materials information</td></tr>
<tr><td>Product Service Code</td><td>Material</td><td>Op. Temp.ºC</td><td>Op. Press barg</td><td colspan="2">Chemical information/Comment/Reference</td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="2"></td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="2"></td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="2"></td></tr>
<tr><td colspan="6">Consequence evaluation</td></tr>
<tr><td colspan="2">Consequence</td><td colspan="2">High/Low</td><td colspan="2">Justification/reasoning/reference</td></tr>
<tr><td colspan="2">Safety</td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td colspan="2">Economic</td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td colspan="2">Environmental</td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td colspan="2">Other</td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td colspan="6">Probability evaluation</td></tr>
<tr><td>Probability</td><td colspan="2">High/Low</td><td>Model (s)</td><td colspan="2">Justification/reasoning/reference</td></tr>
<tr><td>Internal</td><td colspan="2"></td><td></td><td colspan="2"></td></tr>
<tr><td>External</td><td colspan="2"></td><td></td><td colspan="2"></td></tr>
<tr><td>Fatigue</td><td colspan="2"></td><td></td><td colspan="2"></td></tr>
<tr><td></td><td colspan="2"></td><td></td><td colspan="2"></td></tr>
<tr><td colspan="6">Notes/comments:</td></tr>
<tr><td colspan="6">Further Actions:</td></tr>
<tr><td colspan="6">Agreement to evaluation</td></tr>
<tr><td colspan="2">Team</td><td colspan="2"></td><td>Date</td><td></td></tr>
<tr><td colspan="2">Verification</td><td colspan="2"></td><td>Date</td><td></td></tr>
</table>

APPENDIX F
USE OF INSPECTION AND MONITORING

F.1 Introduction

The RBI assessment is used to generate an inspection plan at the desired level of detail. Once the probabilities and consequences of failures are evaluated, and the risks are established, it is necessary to decide whether or not to inspect, when to inspect and how much to inspect. The assessments allow the following parameters to be estimated for each part:

- Degradation mechanism, and hence possible inspection methods, morphology of damage and the expected extent or size of the damage.
- When to apply the inspection – the time when the risk limit is crossed. For the time-dependent rate models, inspection should be scheduled such that the risk limit is not exceeded, with adequate time allowed for keeping track of degradation processes and for carrying out any remedial action. The non-time-dependent mechanisms are not considered suitable for direct control by inspection, but may, for example, require monitoring certain process parameters and/or general visual inspection to check that any premises used in the analysis remain valid, such as good coating.

F.2 Development of inspection plan

The inspection plan should contain the following information as a minimum:

- part identification
- drawing references
- expected degradation mechanism/morphology, location and extent
- monitoring strategies for expected degradation
- inspection location / inspection point
- inspection method
- time to inspect
- reporting
- evaluation
- updates and corrections.

Reference should also be made to minimum operator qualifications, equipment type and calibration requirements, inspection procedure to be used, applicable codes and standards, and other quality-related information.

When carrying out the final inspection planning, the following points should also be considered:

- A component may be subject to different degradation mechanisms that are expected to reach their risk limits at different times. The inspection schedule should take account of these differences by rationalising the timings into suitable groups to avoid otherwise frequent activities on the same components.
- The operator's policy and/or legislation regulating the operation of a field may set specific requirements with respect to inspection. These requirements may be in the form of:
  - how often to inspect certain types of equipment
  - acceptable condition after an inspection, i.e. wall thickness limits.
- Access requirements.
- The need for shutdown of the process during inspection.
- Requirements for detailed inspection drawings.
- Reporting format and reporting limits.

F.3 Expected Degradation Mechanisms/Morphology, Location and extent

Check the expected degradation mechanisms for the component in question and the location of damage.

- Damage type and expected location of damage (top/bottom, welds, components).
- Internal/external damage.
- Variation of degradation with time.

F.4 Monitoring Strategies for Expected Degradation

Different types of monitoring strategies can be implemented to address expected degradation due to defined mechanisms. Monitoring strategies will produce monitoring data regarding degradation rates or key indicators for risk change, such as process changes.

Guidance note:

- Monitoring probes and coupons are generally not intended to provide quantitative degradation rates, but rather to monitor and ensure that the rates are within specified limits. They are also used to monitor inhibitor performance.
- Monitoring of key process parameters that control the rate or onset of degradation can be used to detect the changes in operating conditions, operational practices or reservoir characteristics.
- Different types of degradation control strategies can be implemented to prevent the expected degradation due to defined mechanisms. Control strategies and the effectiveness of these will be assessed in the PoF-analysis.
- Injection of corrosion inhibitor is a typical strategy for control of degradation in offshore processing management.
- Inspection measures the extent of degradation and thus allows comparing the condition revealed by inspection to the design premises. Follow-up on deviation from design premises to operational conditions is a part of Risk-based Inspection Planning.

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F.5 Inspection Location / Inspection Point

A hot spot is a defined part of the inspection object, area or one of typical areas where damage is most likely to occur. The definition of a hot spot is linked to a specified area where CVI or NDT inspection techniques can be applied. GVI, and to some extent CVI, inspection techniques will call for a wider definition of hot spots related to damage. The definitions of hot spots will give guidance to the selection of inspection points.

F.6 Inspection Method

A number of intrusive and non-intrusive methods have been developed to inspect pipes/other static equipment and take the geometric measurements (diameter, wall thickness, metal loss, crack and other defects).

Table F-1 has been developed as an aid to select inspection methods and coverage based on the results from RBI analysis. The sections below describe the contents of different columns of the table.

The use of table is valid under the following assumptions:

- Where different methods are suggested for the same degradation mechanism, the methods should be considered as alternatives to each other.
- The inspection methods are used within their recognised limitations with respect to dimensions and materials of construction for the component subject to inspection.
- Inspection is carried out according to qualified procedures and by qualified personnel.

- All indications of defects found during inspection are followed up by necessary actions to determine defect size and need for increase in extent of inspection.
- When identifying a limited selection of hot spots, it should be recognised that some of the degradation mechanisms will have different PoF for the different types of hot spots listed. The focus should be on the hot spots that are judged to have the highest PoF, but samples of hot spots with a lower PoF should be included for completeness.
- No differentiation is made between the various methods listed for a damage mechanism with respect to PoF in this table, i.e. all methods have been treated as having a PoD of 1 if they have been found suitable to detect the expected damage. Further differentiation in inspection efficiency for the different methods can be made with reference to PoD curves.

F.6.1 Damage Mechanism:

The first column provides guidance for the expected damage mechanism. The details about these mechanism can be found in Appendix A and Appendix B.

F.6.2 Damage Description

The second column of the table summarises the outcome of the damage mechanism. It also gives guidance for the location of hot spots.

F.6.3 Inspection Method

The third column of the table recommends the most suitable inspection method for detecting/ measuring the damage caused by a particular damage mechanism.

The following abbreviations have been used.

GVI	: General visual inspection
CVI	: Close visual inspection
ET	: Eddy current testing
ET-Remote	: Remote Field Eddy Current
MT	: Magnetic particle inspection
PT	: Dye penetration testing
RT	: Radiographic testing
RT-RTR	: Real time radiography
UT	: Ultrasonic testing
UT-Long range	: Creeping/Head Wave Inspection Method
UT-Tubes	: Internal Rotating Inspection System (Ultrasonic)

Guidance note:

- Results from different inspection methods may not be handled in the same data-set.
- Make sure the method, procedure, calibration etc. are the same.
- Any error in the inspection method should be included in the estimation of corrosion rates.

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F.6.4 Inspection Effectiveness

The inspection effectiveness that is required depends upon the requirements of inspection. In this appendix the following inspection effectiveness categories have been defined based upon the examination of hot spots or suspect areas.

- *Highly effective inspection* is used to determine the actual state of degradation when degradation activity is determined. The inspection method will correctly identify the actual damage state in nearly every case.
- *Effective inspection* is used to determine the amount of degradation activity when degradation activity is expected. The inspection method will identify the actual degradation with an uncertainty given by the number of repeated inspections of the same system.
- *Fairly effective inspection* is used to determine if degradation activity is occurring when no significant degradation is expected. The inspection method may give indications if unexpected degradation activity occurs.

The columns four to six can be used as a guidance for the inspection engineer to determine the percentages of hot spots that need to be inspected in order to achieve the desired effectiveness of the inspection.

Guidance note:

- The effect of PoD for the inspection method should be considered because a small damage may cause the risk to exceed limit, yet such damage may not be reliably detected by equipment having low PoD. In such an instance, other risk management methods should be considered.
- In most cases it is recommended to use the category "Effective Inspection" in inspection planning. "Effective inspection" will contribute to the requested reduction in the uncertainty of the degradation rate / damage state. A reduced uncertainty in the damage state will contribute to reduce the risk related to degradation damage.

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F.6.5 Selection Process

The probability of failure evaluation gives an estimation of likely degradation mechanisms, together with their morphology and the data required to estimate the resulting probability of failure. This information can be used to optimise the inspection procedures and techniques, and to select which data should be recorded so that the RBI analysis can be updated after an inspection.

The choice of inspection method is based on optimising several factors that characterise each technique:

- Confidence in detecting the expected damage state.
- Cost of technique/method, including manpower and equipment.
- Extent of maintenance support required (scaffolding, process shutdown, opening of equipment).

Normally, the technique that gives the greatest effectiveness in detection should be chosen – see Section F.6.4. However, it may be more cost-effective to apply a less efficient technique more frequently, and the choice of technique can be based on the following simple cost-benefit analysis:

1) Refer to Table F-1 for the confidence level for the technique chosen.
2) Estimate the cost of carrying out the inspection using the chosen technique.
3) Determine the probability of detection (PoD) for the mean extent of damage expected at the inspection time.
4) Select the technique with the highest value of:

$$\frac{PoD}{\left(Cost \times Confidence\ CoV\right)}$$

The above method is applicable to the first inspection scheduled after the RBI analysis. Prediction of the next inspection timing is estimated once the inspection has been performed, and the above steps repeated using the inspection results.

Note that the inspection procedure should include strict requirements regarding reporting of inspection results, so that the data reported is relevant to, and can be readily used to, update the RBI analyses and hence, plan the next inspection.

F.7 Time to Inspect

The time to inspect has been discussed in detail in Appendix D.

F.8 Evaluation

If internal or external corrosion is detected, then fixed key points at a number of selected locations should be built to monitor the corrosion growth at a frequency decided by the corrosion and inspection engineers; unless this can not be justified within the remaining economic life of the line.

NDT measurements can also be taken in existing corrosion monitoring points to substantiate corrosion coupon readings if applied. This method should be used in all locations where coupon results indicate corrosion in excess of the corrosion design criteria.

Inspection data evaluation should include as a minimum:

— assessment of inspection findings
— estimation of existing minimum wall thickness
— estimation of corrosion rate
— remnant life calculations
— maximum Allowable Working Pressure (MAWP) calculations
— establishment of retiring thickness
— conclusions on integrity status
— recommendations as to further action.

The overall evaluation of integrity status as a result of inspection activity should be carried out and the findings of inspection, including the evaluations, shall be verified.

The effectiveness of the inspection activities should be assessed periodically where the frequency and the revision of planned activities should provide the continued assurance of technical integrity. Reports of the effectiveness of the planned activities in assuring the required integrity and reliability shall be produced and reviewed by management, to ensure that the inspection activities are achieving the required performance.

Part of the review should include the effectiveness of the inspection procedures and routines in ensuring individual equipment is maintained fit for service. This includes the review of failures against the inspection routines to ensure that the routines are adequate for monitoring of such failures.

F.9 Reporting

Data concerning the inspection method and calibrations should be recorded on the report, together with inspector and qualification level. Findings for each equipment item should be entered into the inspection management database.

Inspection reports should give conclusions as to the nature of the indication – relevant / not relevant, crack/planar, pits (with dimensions), local wall thinning (dimensions), general wall thinning (dimensions), crevice, etc. The corrosion and inspection engineer should evaluate the cause of such indications, the inspector shall report only what is found. The precise location of the indication shall be given in relation to a fixed datum, so that the indication can be readily found for re-evaluation. Sketches, photographs, screen pictures etc. should be included in the report where these will aid in interpretation and recording. Where the conclusions are “not acceptable” or “further investigation”, these should be registered in such a way that the follow-up actions are assigned, monitored and actively closed out.

F.10 Updates/Corrections

On the basis that the inspection data has been evaluated and found valid, the wall thickness should be updated to the measured thickness. The probability of failure should be re-calculated using the new thickness data but the original corrosion rate.

Where trending of the data is considered valid and is expected to continue into the future, then the wall thickness should be corrected and a revised corrosion rate should be used to recalculate the probability of failure.

Guidance note:
The corrections can result in either an increase or a decrease in the predicted probability of failure, depending on the inspection outcome.

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F.11 Inspection and Monitoring Data Evaluation/Analysis

F.11.1 General

Inspection results for process equipment usually comprise wall thickness measurements and reports of coating condition. Crack sizes are not normally monitored but repaired as soon as they are found. In all cases, inspection data must be evaluated carefully before it is used to correct the estimates. The following are examples of issues to consider:

— The manner in which the data has been measured and reported

  — Are numerical values given for thickness or damage depth?
  — Is there an adequate reference to the original thickness?
  — Is the extent of damage to coatings given in relation to a numerical scale?
  — What inspection method has been used, and what is its effectiveness in measuring the expected degradation?
  — Has sufficient area of the part been inspected to provide confidence that the result is applicable?
  — Can the results be related to identifiable locations within the part?
  — Are any past data points taken from precisely the same location, so that trending might be meaningful?
  — Has the inspection been carried out where the degradation would be expected?

— The applicability of the data to the situation under evaluation

  — Is the data taken precisely from the part being evaluated, or from the same corrosion group?
  — Where within the part has the data been taken – thickness measurements made on an elbow will not be correlated to the thickness of a straight pipe?

— The applicability of the data to the expected degradation mechanisms

  — Is the measurement location relevant for the expected degradation mechanisms?
  — Does the data relate to internal or external degradation?
  — Does the data measure one or more degradation mechanisms (e.g. CO_2 corrosion and erosion simultaneously at an elbow)?

— Variations and confidence in inspection results – It is common that there is a wide scatter in ultrasonic wall thickness measurements resulting from the inherent inaccuracy of the technique, slight changes in calibration from one inspection to the next, variations due to the operator, and variations due to non-repeatability in location.
— Trending possibilities/limitations – Two-point trending can show marked wall thickness loss rates or wall thickness increase rates. Increasing the number of points used in trending gives a better result, and it is strongly recommended that all relevant data points be plotted so that the best trend can be evaluated by eye as well as spreadsheet algorithm.

— Installation history – The evaluation must also include knowledge of relevant installation history. For example, if many years of operation with effective corrosion inhibition have shown almost no wall loss, yet recently the inhibition equipment has failed, then the low corrosion rate cannot be expected to continue into the future unless inhibition is reinstated.
— Availability of baseline data – Where no baseline inspection data is available, it will be difficult to estimate a corrosion rate as the actual original starting thickness may be unknown and manufacturing tolerances are often large. Note that a comparison between adjacent areas of damaged and sound material can provide an adequate baseline in some cases.

A general checklist for evaluation/analysis of inspection data for use in inspection planning is given below. Together with the points, the general materials knowledge discussed elsewhere in this document should be considered.

F.11.2 Corrosion Monitoring Data

Corrosion monitoring data may be used in conjunction with the inspection data to give a picture of the actual situation. The type of data of interest may be:

— Corrosion coupons
— Direct corrosion rate measurement
— Monitoring of key process parameters
— Chemical analysis of the HC-fluid and the water.

Monitoring probes and coupons are generally not intended to provide quantitative degradation rates, but rather to monitor inhibitor performance or ensure corrosion rates are within specified limits. However, data may be used for this purpose if it is given critical evaluation:

1) Have the probes or coupons been located in the correct position within the system, where the corrosion is expected to occur?

   The placement of a coupon on the top of a pipe where CO_2 corrosion is expected to occur in the water phase running along the bottom will give falsely optimistic results if the coupon does not lie in the water.

2) Has the data been collected and reported correctly?

   This includes the calculation of pH from samples, the correlation of probe/coupon results with process conditions, use of the correct procedure to measure material loss from coupons or relate the signal change in a probe to corrosivity.

Where doubt exists in the use of these data, it should be discounted and new good quality data collected under the supervision of an experienced corrosion engineer. In the meantime, the corrosion rates estimated from the degradation models should be applied until the new, validated data is available.

Monitoring of key process parameters that control the rate or onset of degradation can be used to detect changes in the operating conditions that can affect the probability of failure.

Set points can be specified for relevant parameters and used for triggering inspection based on the PoF limit, rather than regular inspections. For example, temperature is a key parameter for external stress corrosion cracking of stainless steels under wet insulation. Similarly, process instrumentation can be used to indicate when the basis for the RBI analysis is no longer valid – For example, measurement of export gas CO_2 levels can be used as an indicator regarding the CO_2 content throughout the process, with a reanalysis to be carried out when there is a significant change.

F.11.3 Statistical Evaluation of Data

A number of statistical techniques may be used to evaluate the data, the following may be most relevant:

— Regression (trending) analysis of wall thickness
— Estimation of statistical quantities (mean, standard-deviation, skewness, kurtosis) for estimation of extreme values [Kowaka 1994]
— Weibull analysis
— Statistical plotting.

In all cases it is recommended to plot the results in proper graphs, as this will reveal any abnormalities in the data.

F.11.4 Grouping of Data

The data should be grouped appropriately. The following categories are examples of groups that can be relevant when evaluating/analysing inspection data:

— Material and service (or corrosion group/circuit)
— Component type; pipe, vessel, heat-exchanger, etc.
— Age of component if replaced
— Time period if there has been a change in process parameters; water content and chemistry, temperature, fluid composition.

F.11.5 Data Quality Checks

Check the quality of the data. Remove data from the data-set based on one or several of the following:

— Too high rate (i.e. failure within a few months)
— Data for measurement vs. component replacement and age (check that replacement is taken into account)
— Measured thickness vs. nominal wall thickness (data showing an increasing wall thickness may be removed from data-set).

F.11.6 Application of Data between Corrosion Groups/Circuits

Corrosion rate data from one part of the plant may be used for other plants if the conditions are comparable.

Table F-1 Inspection and inspection effectiveness

Damage Mechanism	*Damage Description*	*Inspection Method*	*Highly Effective*	*Effective*	*Fairly Effective*	*Comments*
Uniform & Local CO_2 corrosion Fluid Systems (PL, PT & PW)	— Internal thinning of considerable areas or local internal wall thinning. *Hot spots:* — Bottom of dead legs and other low points where water can accumulate. — Piping and parts of vessels where water can condense. — Welds including HAZ in these areas should be focused on when selecting hot spots for inspection. — Turbulent areas expected to cause the most turbulent flow.	— UT — RT — CVI — Video inspection — Long Range UT	100% of hot spots	30% of hot spots	10% of hot spots	— CO_2 corrosion is only a relevant mechanism for C-steel. — Erosion-corrosion can be present if water content > 20% (full water wetting). — If water content > 5% & < 20% be aware of dead legs. — Be aware of potential erosion problems in well stream (PT). — Be aware of potential MIC problems in semi process (PL, PT & PW).
Uniform & Local CO_2 corrosion Gas Systems (PV)	— Internal thinning of considerable areas or local internal wall thinning. *Hot spots:* — Bottom of dead legs and other low points where water can accumulate. — Piping and parts of vessels where water can condense. — Fluid areas in vessels. — When selecting hot spots for inspection focus should be on welds including HAZ in these areas.	— UT — RT — CVI — Video inspection — Long Range UT	100% of hot spots	30% of hot spots	10% of hot spots	— CO_2 corrosion is only an actual mechanism for C-steel. — Gas can be considered as dry (no water wetting) if temperature is higher than 10°C above dew point, but dead legs must still be considered since they can have temperatures considerably below main process operating temperature.
Sulphide stress cracking (SSC)	— Internal surface breaking crack. *Hot spots:* — Case to case depending upon the design premises and welding QA-log.	— Inspection methods to be chosen from case to case.				— Susceptibility type PoF-model. Not applicable for periodic inspection activities. — SSC is an expected mechanism for all steel grades. — All forms of cracking due to H_2S should be prevented by correct material selection.
Hydrogen Induced Cracking (HIC) Stepwise Cracking (SWC) Stress Oriented Hydrogen Induced Cracking (SOHIC)	— Subsurface laminations or blisters parallel to surface, — Combination of such laminations/blisters and subsurface with cracks normal or parallel to surface. *Hot spots:* — Welds including HAZ (only for SOHIC). — History based on design premises and rolling QA-log.	— Inspection methods to be chosen from case to case.				— The total equipment surface should be considered as suspect area. — HIC, SWC and SOHIC are relevant mechanisms for low-alloy rolled steels only. In general these mechanisms are not recognised as relevant for offshore process piping and vessels. For particular instances where they are considered as relevant, it has to be evaluated whether they are applicable for periodic inspection activities or not under the current conditions. — Hydrogen-induced cracking is caused by nascent hydrogen atoms (H^o), usually produced in aqueous hydrogen sulphide (H_2S). Hydrogen atoms that enter the steel can cause embrittlement and failure.

Table F-1 Inspection and inspection effectiveness (Continued)

Damage Mechanism	*Damage Description*	*Inspection Method*	*Highly Effective*	*Effective*	*Fairly Effective*	*Comments*
Microbiologically Influenced Corrosion (MIC) in CS	— Internal local corrosion randomly distributed. — Local thinning. *Hot spots:* — Dead legs. — Areas where debris can accumulate.	— UT — RT — CVI — Video inspection — Magnetic Flux Leakage (MFL).	100% of equipment surfaces	100% of hot spots		— Susceptibility type PoF-model. — Probability of attack increases with reduced flow. — The corrosion rates due to MIC can be high. — MIC can be occur in anaerobic hydrocarbon or water system when bacteria is present along with sulphates, fatty acids or other nutrition. — Be aware that MIC can be an issue in connection with reproduction of injected seawater. — Be aware that MIC can be an issue for stabilized oil systems, drain systems and water injection systems. — Be aware the MIC can be an issue in the temperature range from 0°C to 80°C. — Be aware that the use of flow improver and other chemicals can contribute to MIC. — Be aware that biocide treatment might not be effective on bacteria protected under debris. Hence, debris cleaning activities have to be performed to ensure effective biocide treatment.
Microbiologically Influenced Corrosion (MIC) in stainless steels	— Internal local corrosion randomly distributed. — Local thinning. *Hot spots:* — Welds including HAZ in dead legs and areas where debris can accumulate.	—				— MIC is generally not expected in other materials than carbon steel in anaerobic systems. — Under rare conditions MIC can be occur in anaerobic hydrocarbon or water system when bacteria is present along with sulphates, fatty acids or other nutrition.
Erosion	— Internal wear of equipment surfaces due to sand in process stream. — Thinning over an area corresponding to impingement. *Hot spots:* — High flow rate and local change of flow rate. — Local change of flow direction. — Different configurations of bends. — Downstream of choke-valves and other control valves. — Areas subject to impingement from jet-nozzles.	— UT — RT — CVI — Video inspection — UT Long range	100% of hot spots	30% of hot spots	10% of hot spots	— Erosion issues are described in DNV-RP-O501. — Key process parameters: — Amount of sand, grain size and flow velocity. — Be aware that valve type can be of importance with regard to erosion. — Installation-specific studies and careful evaluation of local conditions can reduce the number of hot spots in a corrosion circuit down to only a few locations.
General corrosion of CS in utility water systems	— Internal thinning. *Hot spots:* — To be evaluated based on type of water system.	— UT — RT — CVI — Video inspection				— For water systems with higher predictability in location of most severe corrosion, the extent of hot spots can be reduced. — Key parameters are concentration of oxygen and Fe-ions in water.

Table F-1 Inspection and inspection effectiveness (Continued)

Damage Mechanism	*Damage Description*	*Inspection Method*	*Highly Effective*	*Effective*	*Fairly Effective*	*Comments*
Local corrosion of stainless steels in utility water systems	— Internal pitting. *Hot spots:* — Welds including HAZ.	— CVI — UT — RT				— Susceptibility type PoF-model. Not applicable for periodic inspection activities. — Key parameters are concentration of oxygen and Fe-ions in water.
	— Internal thinning in concealed faces forming a crevice. *Hot spots:* — Flanges, screwed connections and other components forming crevices.	— Disassembly and CVI — RT (Screwed connections)				— Susceptibility type PoF-model. Not applicable for periodic inspection activities. — Key parameters are concentration of oxygen and Fe-ions in water.
CUI, CS	— Local corrosion of external surfaces under insulation. — Thinning in patches. *Hot spots:* — Penetrations through deck or wall. — Unpainted surfaces and surfaces with painting in poor condition. — Areas subject to water ingress due to poor installation or condition of vapour barrier or design of equipment. — Low points and water entry points. — Corners where water can collect. — Areas where water condenses.	— Deinsulation and CVI — RT — Real time profile RT — Long rang UT	100% of equipment surfaces	100% of hot spots		— Inspection methods for screening for hot spots: CVI, thermography, real time profile RT or humidity measurements in insulation. — Not that field welds can be subjected to CUI due to substandard surface treatment or insulation work. — Note that CUI has been seen independent of insulation material used. — Note that presence and functionality of drainage facilities can be of importance to CUI. — Note that severe CUI may occur in the sections where pipe crosses through a wall or a deck.
CUI, stainless steels	— Local corrosion and pitting of external surfaces under insulation. — Local pitting. *Hot spots:* — Welds including HAZ and areas subject to heavy cold work that are unpainted or with painting in poor condition, located in following locations: — Areas subject to water ingress due to poor installation or condition of vapour barrier or design of equipment. — Low points and water entry points. — Corners where water can collect. — Areas where water condenses.	— Deinsulation and CVI — Deinsulation and PT				— Susceptibility type PoF-model. Inspection for conditions causing corrosion followed by actions to remove cause might give reduction in PoF. — Inspection methods for screening for hot spots: CVI, thermography or humidity measurements in insulation. — Not that field welds can be subjected to CUI due to substandard surface treatment or insulation work. — Note that CUI has been seen independent of insulation material used. — Note that presence and functionality of drainage facilities can be of importance to CUI.

Table F-1 Inspection and inspection effectiveness (Continued)

Damage Mechanism	*Damage Description*	*Inspection Method*	*Highly Effective*	*Effective*	*Fairly Effective*	*Comments*
ESCC under insulation	— External surface breaking crack. *Hot spots:* — Welds incl. HAZ and areas subject to heavy cold work that are unpainted or with painting in poor condition, located in following locations: — Areas subject to water ingress due to poor installation or condition of vapour barrier or design of equipment. — Low points, corners and other places where intruding water can collect. — Wet surfaces with chloride deposits.	— Deinsulation and ET — Deinsulation and PT — Deinsulation and creep wave UT				— Susceptibility type PoF-model. Inspection for conditions causing corrosion followed by actions to remove cause might give reduction in PoF. — Inspection methods for screening for hot spots: CVI, thermography, humidity measurements in insulation. — Key parameters are material surface temperatures / operating temperatures. — Not that field welds can be subjected to ESCC due to substandard surface treatment or insulation work. — Note that ESCC has been seen independent of insulation material used. — Note that presence and functionality of drainage facilities can be of importance to ESCC.
External corrosion of uninsulated CS	— Uniform and local corrosion of external surfaces. — Thinning in patches. *Hot spots:* — Unpainted surfaces or surfaces with painting in poor condition with the following conditions: — Corners where water can collect. — Areas where water condenses. — Under deposits of dirt etc. — Drips onto hot piping.	— CVI	100% of equipment surfaces			— Inspection methods for screening for hot spots: GVI. — Note that field welds and repair welds can be subjected to external corrosion due to substandard surface treatment. — Note that surface treatment maintenance is vital for control of external corrosion.

Table F-1 Inspection and inspection effectiveness (Continued)						
Damage Mechanism	*Damage Description*	*Inspection Method*	*Highly Effective*	*Effective*	*Fairly Effective*	*Comments*
External corrosion of uninsulated stainless steels or titanium External crevice corrosion	— Local corrosion and pitting of external surfaces. — Local pitting. *Hot spots:* — Discolouration. Welds including HAZ, areas subject to heavy cold work or areas contaminated with CS material from grinding etc., without painting or with painting in poor condition and the following conditions: — Corners where water can collect. — Areas where water condenses. — Under deposits of dirt etc. — Drips onto hot piping.	— CVI — PT	100% of hot spots			— Inspection methods for screening for hot spots: GVI. — Note that field welds and repair welds can be subjected to external corrosion due to substandard surface treatment. — Note that surface treatment maintenance is vital for control of external corrosion.
	— Local thinning in concealed faces forming a crevice. *Hot spots:* — Flanges and other details forming crevices. — Under clamps. — Under adhesive tape or other markings.	— Disassembly and CVI — RT (Screwed connections) — CVI combined with creep wave or long range UT	100% of hot spots			— CVI to be followed up by disassembly or NDT if visual indications of corrosion are detected. — Note that design solutions and passivation control can be of importance to local corrosion.
Oxygen contamination corrosion	— Internal thinning of considerable areas — Local internal wall thinning.	— CVI — UT — RT				— No PoF-model available for this degradation mechanism. — Note that the combined effect of oxygen and CO_2 on the corrosion rate will tend to increase the overall rate. — Be aware of the possibility of oxygen contamination due to use of platform nitrogen as purge gas.
Elemental sulphur corrosion	— Local internal wall thinning.	— CVI — UT — RT				— No PoF-model available for this degradation mechanism. — Note the possibility of formation of elemental sulphur due to a reaction with oxygen in a wet gas environment. — Note that if chloride is present the corrosion rate can be accelerated.
Local corrosion in connection with injection or mixing points	— Local internal wall thinning. *Hot spots:* — Injection and mixing points including downstream piping and bends.	— CVI — UT — RT	100% of hot spots			— No PoF-model available for this degradation mechanism. — Be aware that the corrosion rate can be accelerated due to turbulence.

Table F-1 Inspection and inspection effectiveness (Continued)

Damage Mechanism	*Damage Description*	*Inspection Method*	*Highly Effective*	*Effective*	*Fairly Effective*	*Comments*
Galvanic corrosion	— Local corrosion due to contact between different materials (Ref. the galvanic series). — Internal and external. *Hot spots:* — Areas on the least noble metal close to material breaks.	— CVI — UT — RT	100% of hot spots			— No PoF-model available for this degradation mechanism. — Consider the material design, control and focus the follow-up on isolation spool pieces. — Note the potential of corrosion of plugs with reference to plug type and plug material.
Weld corrosion	— Local corrosion due to use of deposited metal not according to specification. — Internal and external.	— CVI — UT — RT	100% of hot spots			— No PoF-model available for this degradation mechanism. — Control and follow-up should be focused on welding processes and deviation log.
Fretting corrosion	— Local corrosion due to fretting. — Valid for both piping and vessels. — Internal and external. *Hot spots:* — To be evaluated based on Design, Fabrication, Installation and Operation (DFI&O) documentation.	— CVI — UT — RT	100% of hot spots			— No PoF-model available for this degradation mechanism. — Control and follow-up should be focused on equipment installation and operation.
Corrosion under plate cladding	— Local corrosion due to defects in plate cladding of equipment. *Hot spots:* — To be evaluated based on DFI&O documentation.	— UT — CVI — ET		100% of hot spots		— No PoF-model available for this degradation mechanism. — Focus on the control and follow-up on cladding installations.
Weld overlay corrosion	— Local corrosion due to defects in weld overlay of plates, nozzles and flanges. *Hot spots:* — To be evaluated based on DFI&O documentation.	— UT — CVI — ET — PT		100% of hot spots		— No PoF-model available for this degradation mechanism. — Control and follow-up to be focused on weld overlay installations. — Severe corrosion has been seen due to weaknesses of weld overlay.
Flange corrosion	— Local corrosion due to gasket deformation or use of wrong gasket. *Hot spots:* — To be evaluated based on DFI&O documentation.	— CVT	100% of hot spots			— No PoF-model available for this degradation mechanism. — Control and follow-up on preservation of flanged connections. Focus on the correct usage of gaskets and bolts. — There is a possibility of corrosion of the outer part of the seal assembly.
Bolt corrosion	— Local corrosion due to defect in bolt material, galvanizing or to high utilization of threads. *Hot spots:* — To be evaluated based on DFI&O documentation.	— CVI — PT — ET	100% of hot spots			— No PoF-model available for this degradation mechanism. — Severe corrosion of galvanized bolts can occur resulting in degradation of galvanization.

Table F-1 Inspection and inspection effectiveness (Continued)

Damage Mechanism	*Damage Description*	*Inspection Method*	*Highly Effective*	*Effective*	*Fairly Effective*	*Comments*
Fatigue	— Internal or external cracking of cyclically- stressed components. — Surface breaking crack from external surface or from pre-existing defect. *Hot spots:* — Welds in systems with cyclic loads in connection with: — Clamped supports, branching points nozzle attachments and other fixing points. — Marked changes in dimensions. — “Sockolets” for heavy equipment mounted to piping through smaller dimension piping. — Smaller diameter branching connections. — Internal equipment vessels.	— Measurement of oscillating stresses				— Inspection for cracking will not give significant reduction in PoF for components with unacceptable oscillating stresses, but inspection for conditions causing vibrations followed by actions to remove cause might give reduction in PoF. — Inspection methods for screening for hot spots: GVI. — Focus on the design, installation, supporting and weld grinding. — There is a possibility of fatigue internally in static equipment due to liquid slugs and thermal cyclic processes.
Brittle fracture	— Severe defect due to uncontrolled material embrittlement. *Hot spots:* — Hot spots to be evaluated based on DFI&O documentation.	—				— No PoF-model available for this degradation mechanism. — Focus on the conditions that can lead to brittle fracture.
Internal damage to shell and tube heat exchangers	— Internal defects due to design and fabrication, installation or in-service stress factors.	— CVI	100% of hot spots			— No PoF-models available for these degradation mechanisms. — There is a possibility of corrosion between tube and tube sheet. — There is a possibility of cracking between tube and tube sheet. — There is a possibility of deformation (cracking) of tubes. — There is a possibility of corrosion if cracking or damage to internal lining in channel / tube sheet. — There is a possibility of damage (fatigue / tear out) to the deviation sheet of the channel. — There is a possibility of damage to tubes and tie rods due to lack of impingement protection. — There is a possibility of burst of tubes due to hydrate formation.

Table F-1 Inspection and inspection effectiveness (Continued)

Damage Mechanism	*Damage Description*	*Inspection Method*	*Highly Effective*	*Effective*	*Fairly Effective*	*Comments*
Internal corrosion of CS vessels	— Uniform and local corrosion of internal surfaces. — Thinning in patches. *Hot spots:* — Unpainted surfaces or surfaces with painting in poor condition with the following conditions: — Corners where water can collect. — Areas where water condenses. — Under deposits of dirt etc.	— CVI	100% of equipment surfaces			— Inspection methods for screening for hot spots: GVI. — Field welds and repair welds can be subjected to corrosion due to substandard surface treatment. — Surface treatment maintenance is vital for control of corrosion. — If anodes are installed then the consumption of anodes can predict the corrosivity.
Mechanical damage	— Internal or external local defects due to mechanical impact under fabrication, installation or in service.	— CVI	100% of hot spots			— No PoF-model available for this degradation mechanism. — Follow-up to be focused on in-service mechanical damage. — There is a possibility of mechanical damage internally in static equipment due to liquid slugs and thermal cyclic processes. — Be aware of the potential for severe defect due to uncontrolled hydrate formation.

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