



Best practice for risk based inspection as a part of plant integrity management

Prepared by **TWI and
Royal & SunAlliance Engineering**
for the Health and Safety Executive

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Best practice for risk based inspection as a part of plant integrity management

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This report discusses the best practice for the application of Risk Based Inspection (RBI) as part of plant integrity management, and its inspection strategy for the inspection of pressure equipment and systems that are subject to the requirements for in-service examination under the Pressure Systems Safety Regulations 2000 (PSSR). It can also apply to equipment and systems containing hazardous materials that are inspected as a means to comply with the Control of Major Accident Hazards Regulations (COMAH).

One of the main themes of the report is the amount of information that is known about an item of equipment and conversely the identification of where there is a lack of information, which may make the RBI invalid. The report considers the application, data requirements, team competences, inspection plan (including NDT techniques and reliability) and overall management of the RBI process.

An audit tool is given in the Appendices order to assist the evaluation the RBI process. This contains a flow diagram followed by a series of questions and a commentary relating to each stage. The commentary summarises the best practice discussed in the main text.

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EXECUTIVE SUMMARY

Aims and Objectives

Owners and users of plant ('Duty Holders' within this report) have the option to manage the integrity of their plant and plan inspection from assessments of the risks of failure. They need to be able to demonstrate that the risk assessment and inspection planning processes are being implemented in an effective and appropriate manner. The aim of this report is to assist Duty Holders and regulators identify best practice for plant integrity management by risk based inspection (RBI).

The Health and Safety Executive (HSE) commissioned this project within its Mainstream Research Programme 1998/99. The specific objectives are:

- To define the process and key elements of RBI.
- To give guidance on the information required and methods for RBI.
- To suggest best practice for the proper implementation of RBI.
- To provide an audit tool to enable evaluation of RBI.

Scope

This report applies to plant integrity management and inspection of pressure equipment and systems that are subject to the requirements for in-service examination under the Pressure Systems Safety Regulations 2000 (PSSR). It also applies to equipment and systems containing hazardous materials that are inspected as a means to comply with the Control of Major Accident Hazards Regulations (COMAH). The principles and practice of RBI within this report are also applicable to the management of other safety-related structures and equipment, for example lifting and fairground equipment.

The report views RBI as one of a range of measures within the wider process of plant integrity management. It evaluates RBI within the context of the current regulatory framework and focuses on the form and management of the RBI process rather than on specific techniques or approaches. After an introductory chapter defining the basis of the report, the following nine chapters deal with the different stages of the process.

An example is given of a risk assessment carried out by Royal and SunAlliance Engineering as an authoritative technical review of examination intervals of a plant. It highlights the importance of the multi-disciplinary team approach to RBI and the role of the Competent Person. It shows how, as a result of the risk assessment, examination intervals could be extended for some items of equipment.

An audit tool is given in order to assist Duty Holders and regulators evaluate the process of plant integrity management by RBI. This contains a flow diagram followed by a series of questions and a commentary relating to each stage. The commentary summarises the best practice discussed in the main text.

Duty Holders inspect plant to manage the risk of failure for many reasons. Whilst this report is primarily concerned with risks to Health and Safety, it recognises the responsibilities of Duty Holders to protect the environment and manage their business effectively and efficiently. The common goal is to prevent failure that could cause danger and damage.

Main Themes

One of the main themes of the report is the amount of information that is known about an item of equipment and conversely the identification of where there is a lack of information. Even when information appears to be known, the risk based approach requires that the quality and veracity of the information is tested and validated. Risk is increased when there is lack of, or uncertainty in, the key information required to assess integrity.

In terms of plant integrity, key information is generated from the design, operational experience and inspection records, and knowledge of the deterioration mechanisms and the rate at which deterioration will proceed. This knowledge enables current and future fitness-for-service to be assessed. Inspections can then be planned at appropriate intervals using inspection methods that are able to detect the type and level of deterioration anticipated.

The PSSR enable a risk-based approach to be used for the planning of inspection. As goal-setting regulations, they allow the Duty Holder and Competent Person flexibility in deciding upon a suitable written scheme of examination in terms of the equipment to be inspected and the frequency and nature of examination. The information generated by the risk assessment can be used to aid these judgements and to achieve a safe and suitable scheme that is not unduly restrictive.

The report discusses the capability of various NDT methods and the means that Duty Holders can use to assure themselves of the reliability of their inspections. The status of acoustic emission, long range ultrasonic and other remote and non-invasive techniques is reviewed, together with the benefits of inspection qualification.

Risk changes with time either because the equipment or plant conditions physically alter, or because new information becomes available. The report highlights the importance of feedback and the re-assessment of risk during plant life. This is particularly pertinent when inspection intervals are long.

Application

The report will be of use to engineers responsible for planning inspection of safety critical plant. Regulators, safety managers, site inspectors and others involved in industrial risk assessment will also find the report useful. The advice given in the report is not intended to be prescriptive, but to be used as a guide to best practice, to be adapted to suit specific circumstances, and to be interpreted in terms of a goal-setting safety regime.

1. INTRODUCTION

1.1. BACKGROUND

In-service inspection of pressure systems, storage tanks and containers of hazardous materials has traditionally been driven by prescriptive industry practices. Statutory inspection under Health and Safety legislation has long been a requirement for boilers, pressure systems and other safety critical equipment.

Prescriptive practices fixed the locations, frequency and methods of inspection mainly on the basis of general industrial experience for the type of equipment. These practices, although inflexible, have, on the whole, provided adequate safety and reliability.

Prescriptive inspection has a number of short-comings. In particular, it does not encourage the analysis of the specific threats to integrity, the consequences of failure and the risks created by each item of equipment. It lacks the freedom to benefit from good operating experience and focussing finite inspection resources to the areas of greatest concern.

Goal setting safety legislation for pressure systems was first introduced in 1989 (1.1) and retained in the Pressure Systems Safety Regulations (PSSR) 2000 (1.2). This has enabled a move towards inspection strategies based on the risk of failure. The legislation leaves the user or owner, in conjunction with the Competent Person, with the flexibility to decide a 'suitable' written scheme for examination to prevent danger on the basis of the available information about the system and best engineering practice.

This trend towards a risk based approach is being supported by extensive plant operating experience, improved understanding of material degradation mechanisms, and the availability of fitness-for-service assessment procedures. At the same time, developments in non-destructive testing (NDT) technology have increased the scope and efficiency of examinations that can be undertaken. Inspection trials have produced a greater appreciation of the limits of NDT performance and reliability (1.3).

Industry is recognising that benefit may be gained from more informed inspection (1.4). Certain sectors of industry, particularly the refining and petrochemicals sectors, are now setting inspection priorities on the basis of the specific risk of failure. Improved targeting and timing of inspections offer industry the potential benefits of:

- Improved management of Health and Safety and other risks of plant failure.
- Timely identification and repair or replacement of deteriorating equipment.
- Cost savings by eliminating ineffective inspection, extending inspection intervals and greater plant availability.

Owners and users of plant ('Duty Holders' within this report) have the option of managing the integrity of their plant and planning inspection based on risk assessments. They need to be able to demonstrate that the risk assessment and

inspection planning processes are being implemented in an effective and appropriate manner.

Inspection is usually one part of an integrated integrity management strategy for managing the risk of failure containing other control measures as may be appropriate. These normally include routine and preventative maintenance, and the inspection and maintenance functions are being increasingly linked within a common framework.

The aim of this report is to assist industry and the regulator identify best practice for plant integrity management by risk based inspection (RBI). It will be of particular use to plant engineers responsible for inspection planning. It will also interest safety managers, site inspectors and others involved in industrial risk assessment.

1.2. OBJECTIVES

The Health and Safety Executive (HSE) commissioned this project within its Mainstream Research Programme 1998/99 (1.5). Broad requirements were interpreted in the formal proposal (1.6). This led to the specific objectives of the work as follows:

- To define the process and key elements of RBI.
- To give guidance on the information required and methods for RBI.
- To suggest best practice for the proper implementation of RBI.
- To provide an audit tool to enable evaluation of RBI.

1.3. EQUIPMENT COVERED

This report applies to pressure equipment and systems that are subject to the requirements for in-service inspection under the Pressure Systems Safety Regulations 2000 (PSSR) (1.2). It applies to fixed pressure vessels and boilers, pressurised and refrigerated storage spheres, together with associated pipework, valves, pumps, compressors, and including hoses and bellows. Protective devices (safety valves, bursting discs etc) are covered by the PSSR and are also within the scope of this report.

The Control of Major Accident Hazards Regulations (COMAH) (1.7, 1.8) cover the control of major accident hazards at installations as a whole. Such installations may include atmospheric storage tanks, process pipework and other equipment containing of flammable or toxic and other hazardous materials. While in-service inspection of such equipment is not a specific requirement of the COMAH regulations, when this is done in order to meet the more general requirement to demonstrate adequate confidence of integrity, the guidance given this report can be applied.

This report has been written largely with boilers and large power and chemical plant in mind. It is, however, intended to apply to all pressure systems and containers requiring integrity management. The principles are also applicable to other safety related structures and equipment, for example lifting and fairground equipment.

1.4. DEFINITIONS

Within this report, any unintentional release of stored energy and/or hazardous contents from a pressure system or containment constitutes a failure. Failure usually involves a breach in the containment boundary and a release of contents into the environment. In extreme cases, stored energy may be released as a high pressure jet, missiles, structural collapse or pipe whip and contents may be flammable and/or toxic.

The probability of failure is the mean frequency or rate with which the specified failure event would be expected to occur in a given period of time, normally one year.

The consequence of failure through the unintentional release of stored energy and hazardous material is the potential for harm. Duty Holders have a responsibility to assess the potential harm to the Health and Safety of employees and/or the public, and to the environment from pollution and other damage. They may also legitimately consider the consequences of failure on their business, such as the costs of lost production, repair and replacement of equipment and the damage to of the company reputation.

The risk of failure combines the probability of failure with a measure of the consequences of that failure. If these are evaluated numerically, then the risk is defined as the product of the probability of failure rate and the measured consequence. There can be different risks for different measures of consequence.

Despite this definition, risk is often assessed qualitatively without this formal factoring. In this situation, risk is the combination of the qualitatively assessed likelihood and consequences of failure and is often presented as an element within a likelihood-consequence matrix. (Within this report, ‘probability’ is used in association with quantitative assessments and ‘likelihood’ is used in association with qualitative assessments of risk).

1.5. CAUSES OF FAILURE

Root causes of failure of pressure systems, tanks and other containers include:

- Inadequate design and/or material for the loading and operating environment.
- Incorrect and/or defective manufacture.
- Unanticipated in-service deterioration such as corrosion or fatigue cracking.
- System errors in operation or maintenance or over-pressure protection.
- Malfunction of instrumentation, control systems or feed and utility supplies.
- Human factors including deliberate damage.
- External events such as fire, impacts or storms.

An integrated integrity management strategy will contain measures that address and mitigate the possibility of these root causes of failure. Design reviews, manufacturing quality assurance, operating training, and systems analyses are examples of such measures. In-service inspection is a backstop to prevent failure

when a root cause has led to deterioration from the design intent or the as-manufactured condition.

In this report, ‘deterioration’ is defined as damage, defects or degradation including:

- Macroscopic damage such as dents or gouges, bulging, deformation.
- General or localised wall thinning and pitting.
- Material flaws, cracks, and welding defects.
- Degradation of material properties due to changes in the material microstructure.

Deterioration can result from discrete events (e.g. welding flaws, impact damage) and the equipment may remain in that condition without further change. It commonly relates to age and service, initiating or becoming worse with time. Sometimes a discrete event can lead to more rapid deterioration, such as the loss of water chemistry control.

In order for inspection to be effective, the inspection periodicity must be sufficiently short in relation to the time between the deterioration becoming detectable and the on-set of failure. Inspection techniques must be selected that are capable of detecting the deterioration of concern at a sufficiently early stage with sufficient reliability.

1.6. RISK BASED INSPECTION

Within this report, the term ‘inspection’ refers to the planning, implementation and evaluation of examinations to determine the physical and metallurgical condition of equipment or a structure in terms of fitness-for-service. Examination methods include visual surveys and the raft of NDT techniques designed to detect and size wall thinning and defects, such as ultrasonic testing and radiography. Other techniques might also include surface replication, material sampling and dimensional control.

In-service inspection is most valuable where there is uncertainty about the operating conditions, or their effect on the materials, particularly where the conditions are such as to suggest that deterioration is taking place. Even when the service conditions and effects are well understood, such as in high integrity plant, inspection can provide continuing assurance of design assumptions and manufacturing integrity. Inspection is also a priority for equipment where the fabrication, inspection or operating history is unknown, where there is inadequate maintenance, or where there is lack of the materials data required for assessing fitness for service.

Risk based inspection involves the planning of an inspection on the basis of the information obtained from a risk analysis of the equipment. The purpose of the risk analysis is to identify the potential degradation mechanisms and threats to the integrity of the equipment and to assess the consequences and risks of failure. The inspection plan can then target the high risk equipment and be designed to detect potential degradation before fitness-for-service could be threatened.

Sometimes the term risk informed inspection is used. This was first introduced by the US Nuclear Regulatory Commission in order to emphasise the link but not a direct correlation between risk and inspection. If risk based inspection is understood to be inspection planned on the basis of information obtained about the risk, then the two terms are synonymous.

Inspection provides new information about the condition of the equipment. This may be better or worse or the same as previously estimated, but the effect is to reduce the prior uncertainty. New information can therefore change the estimated probability of failure.

An impending failure and its consequences are not prevented or changed by risk based inspection unless additional mitigating actions are taken. Inspection is an initiator for actions such as the repair or replacement of deteriorating equipment, or a change to the operating conditions. By identifying potential problems, risk based inspection increases the chances that mitigating actions will be taken, and thereby reduces the frequency of failure.

1.7. PROCESS OF RISK BASED INSPECTION

The process of risk based inspection should form part of an integrated strategy for managing the integrity of the systems and equipment of the installation as a whole. Its aim is to focus management action on prioritising resources to manage the risk from critical items of equipment.

Risk based inspection is a logical and structured process of planning and evaluation. Figure 1.1 shows the main stages and links within the process as suggested best practice. Each stage of the process is covered within this report and the audit tool in Appendix B.

First, the requirements for plant integrity management by RBI are established within the context of existing regulations, inspection codes and practices. Chapter 2 reviews the regulations, guidance and practices relating to risk assessments and RBI.

The next stage is to identify the systems, the system boundaries and the equipment within them requiring integrity management. Drivers, criteria and limitations for a risk based approach to inspection planning must be ascertained as RBI may not always be possible or appropriate. These aspects are considered in Chapter 3.

For risk based inspection, information and opinions from several functions and disciplines are normally needed. It is recommended that these were best obtained from a team of relevant individuals. Chapter 4 reviews the competencies and roles that may be required within the composition of the team and the associated management issues.

Risk based inspection requires a wide range of information in order to assess the probability and consequences of equipment failure and develop an inspection plan. Guidance is given in Chapter 5 on the scope and quality of information necessary. A

plant database containing an inventory of the equipment and associated information is a useful way of managing the relevant data.

Chapter 6 deals with risk analysis and the ranking and categorisation of the equipment/sites having the highest risks of failure. Procedures and information are given in Appendix D for identifying potential damage, defects or degradation. Methods for assessing the probability and consequences of equipment failure are discussed, and descriptive qualitative assessment criteria are defined.

The information and associated uncertainties identified by the risk analysis about potential deterioration are used to develop an integrity management strategy and appropriate inspection plan. Chapter 7 shows how a risk analysis may influence written schemes of examination in accordance with the Pressure Systems Safety Regulations.

In order for inspection to be an effective part of integrity management, the techniques and procedures used must be capable of achieving a reliable examination. The techniques and procedures must therefore be matched to the potential deterioration identified by the risk analysis. Chapter 8 provides information about the capability of NDT techniques and considers ways that Duty Holders and inspection companies can use to demonstrate the reliability of their inspection.

Assessment of the examination results and fitness-for-service are essential parts of the RBI process. For equipment where fitness-for-service cannot be assured, repairs, modification or changes to operating conditions may be recommended. Chapter 9 highlights the need for feedback of the examination results and any changes to the plant into the plant database and the risk analysis before the next inspection interval is set in the future inspection plan.

In order to complete the cyclic process of risk based inspection, it is necessary to review the effectiveness and management of the RBI planning process. Documentary evidence is needed to provide an audit trail. Guidance is given in Chapter 10.

Appendix A gives a case study that illustrates good practice in risk assessment for inspection planning. Appendix B provides an audit tool with sample questions to determine how well RBI is being performed.

1.8. REFERENCES FROM CHAPTER 1

1.1 Pressure Systems and Transportable Gas Containers Regulations 1989 (SI-1989-2169). Revoked by reference 1.2.

1.2 Pressure Systems Safety Regulations 2000 (SI-2000-128), ISBN 011 08 58360, published by The Stationary Office.

1.3 Final Report Programme for the Assessment of NDT in Industry (PANI)', AEA Technology, published by HSE 1999.

1.4 'Extending run lengths of existing pressure equipment'. Proceedings of Seminar S504 at the Institution of Mechanical Engineers, London, 28 October 1997.

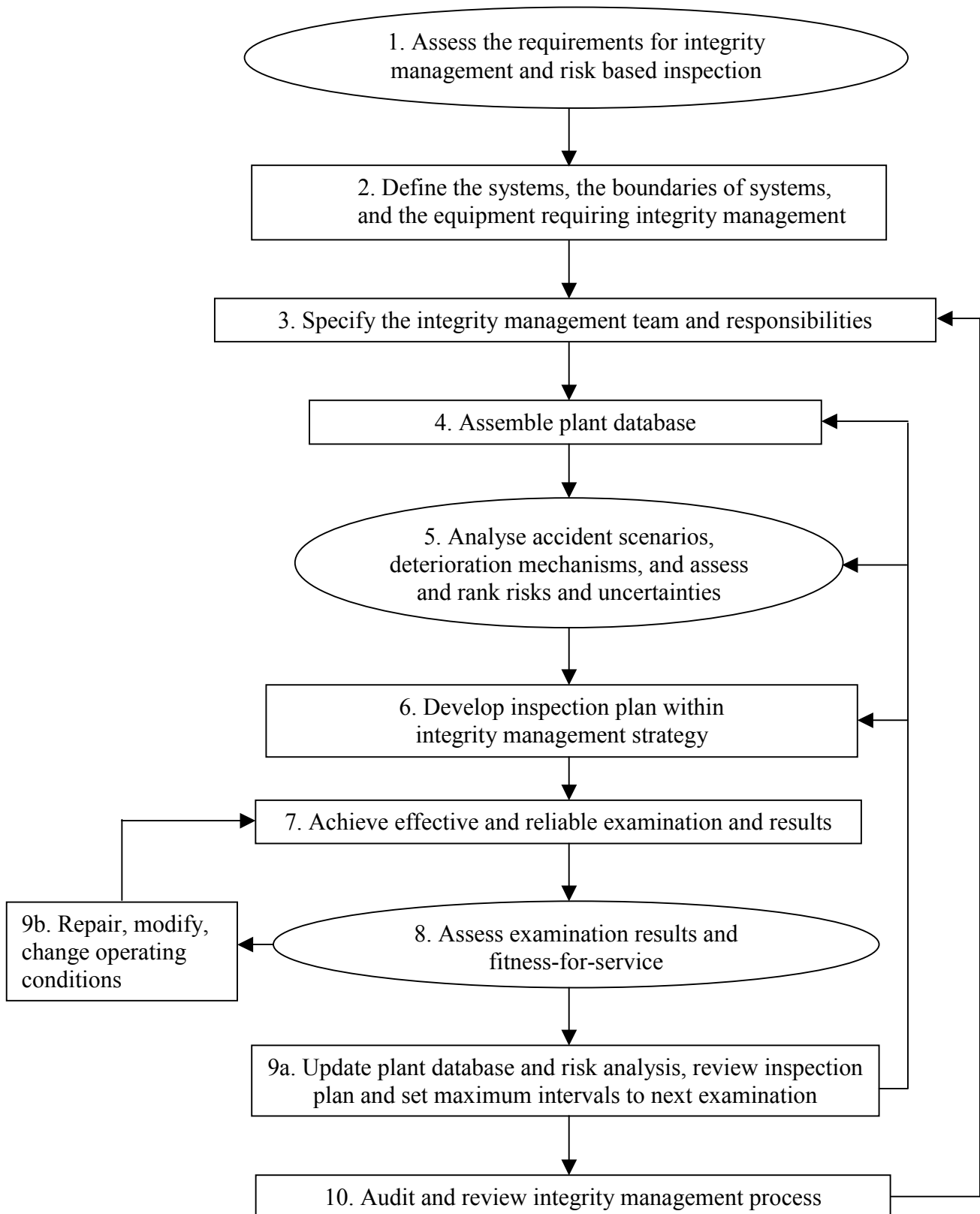
1.5 Mainstream Research Market 1998/99. HSE Publication C10 2/98. 1998.

1.6 'Guidance for Risk Based Inspection', TWI/RSAE Proposal RP/SID/6306 November 1998.

1.7 Control of Major Accident Hazard Regulations 1999 (SI-1999-743), ISBN 011 08 21920, published by The Stationary Office.

1.8 The Planning of Control of Major Accident Hazard Regulations 1999 (SI-1999-981), ISBN 011 08 23672, published by The Stationary Office.

Fig. 1.1 Process diagram for plant integrity management by risk based inspection



2. REGULATION AND GUIDELINES

2.1. HEALTH AND SAFETY LEGISLATION ON INDUSTRIAL EQUIPMENT

The Health and Safety at Work etc Act 1974 (HSW Act) states that every employer has a duty to ensure, as far as is practicable, the health, safety and welfare at work of his employees. Failure to comply with the general duties of the Act or specific requirements of the regulations may result in legal proceedings being taken. The judgement of what is reasonably practicable requires the employer to weigh up the seriousness of the risk against the difficulty and the cost of removing it (2.1).

In addition to this UK legislation, the European Commission has introduced a series of European Health and Safety Directives. These Directives are European Law and are being implemented by every member state of the European Union. Within the UK, implementation of these Directives is within the existing Health and Safety framework.

In some areas the general duties of the HSW Act are supplemented by specific requirements in Regulations made under the HSW Act. Regulations relevant to pressure systems and the control of major accident hazards resulting from containers of hazardous materials are considered below. These specify goals for the assurance of safety that can be met through the examination of plant.

Some regulations, including those dealing with pressure systems, are published in conjunction with supporting information referred to as Approved Code of Practice (ACoP), Guidance and Guide. The ACoP provides practical advice on how to comply with the Regulations, and if followed is sufficient to comply with the law. Guidance material describes practical means of complying with the Regulations, and although it is not compulsory it is seen as best practice.

2.1.1. Pressure Systems Safety Regulations 2000 (SI 2000 No. 128)

The Pressure Systems Safety Regulations (2.2) (PSSR) states that their aim to prevent serious injury from the hazard of stored energy as a result of the failure of a pressure system or one of its component parts. With the exception of the scalding effects of steam, the PSSR do not consider the hazardous properties of the system contents released following failure. Control of hazardous materials that are highly toxic, flammable or where they may create a further major hazard is subject to separate legislation that must take into account when addressing the risk.

The PSSR are 'Goal Setting', that is, they state what the desired end result is but do not give any prescriptive method of achieving that result. Regulation 4 states that 'The pressure system shall be properly designed and properly constructed from suitable material, so as to prevent danger.' The regulations therefore allow the Duty Holder the flexibility to meet this requirement in any way considered appropriate. The ACoP and Guidance offer further advice as to how this regulation can be complied with.

The regulations interpret 'examination' as 'a careful and critical scrutiny of a pressure system or part of a pressure system, in or out of service as appropriate,

using suitable techniques, including testing where appropriate, to assess its actual condition and whether, for the period up to the next examination, it will not cause danger when properly used’.

The responsibility of specifying the nature and frequency of examinations and any special measures needed to prepare the system for safe examination is placed with the Competent Person. Further guidance is provided in the ACoP. Although this does not specify what the examination should consist of, it states that the nature of the examination may vary depending on the circumstances.

Examination can vary from out-of-service examination with the system stripped down, to an in-service examination with the system running under normal operating conditions. The Competent Person should have sufficient practical and theoretical knowledge and actual experience of the type of system under examination to decide what is appropriate. The examination must enable defects or weaknesses to be identified for the Competent Person to make an assessment made of their significance in terms of integrity and safety of the plant.

When deciding on the periodicity between examinations, the aim should be to ensure that examinations are carried out at realistic frequencies to identify, at an early stage, any deterioration that is likely to affect the safe operation of the system. In other words, the examination frequency should be consistent with the risk of system failure associated with a particular item.

It is worth noting that ‘risk’ is not defined within the PSSR. However, the ACoP provides advice as to the factors that should be taken into account when deciding on an appropriate interval between examinations. It acknowledges that there can be no hard and fast rule in determining the appropriate frequency except that that the Competent Person should use their judgement and experience.

It can be seen from the foregoing, that although the requirement for a ‘risk assessment’ to be carried out is neither clearly stated nor defined within the PSSR, it is inferred throughout the regulations that an assessment of the risk of plant failure is essential.

2.1.2. Pressure Equipment Regulations 1999 (SI 1999/2001)

The European Pressure Equipment Directive (PED) (2.3, 2.4) was implemented in the UK in 1999 by the Pressure Equipment Regulations (PER). The aim of the Directive and the Regulations are to remove barriers to trade of pressure equipment. They apply to the design, manufacture and conformity assessment of pressure equipment and assemblies of pressure equipment with a maximum allowable pressure greater than 0.5 bar.

These regulations identify under the Essential Safety Requirements that ‘Pressure equipment must be designed and constructed so that all necessary examinations to ensure safety can be carried out’ and that ‘means of determining the internal condition of the equipment must be available where this is necessary to ensure the continued safety of the equipment.’

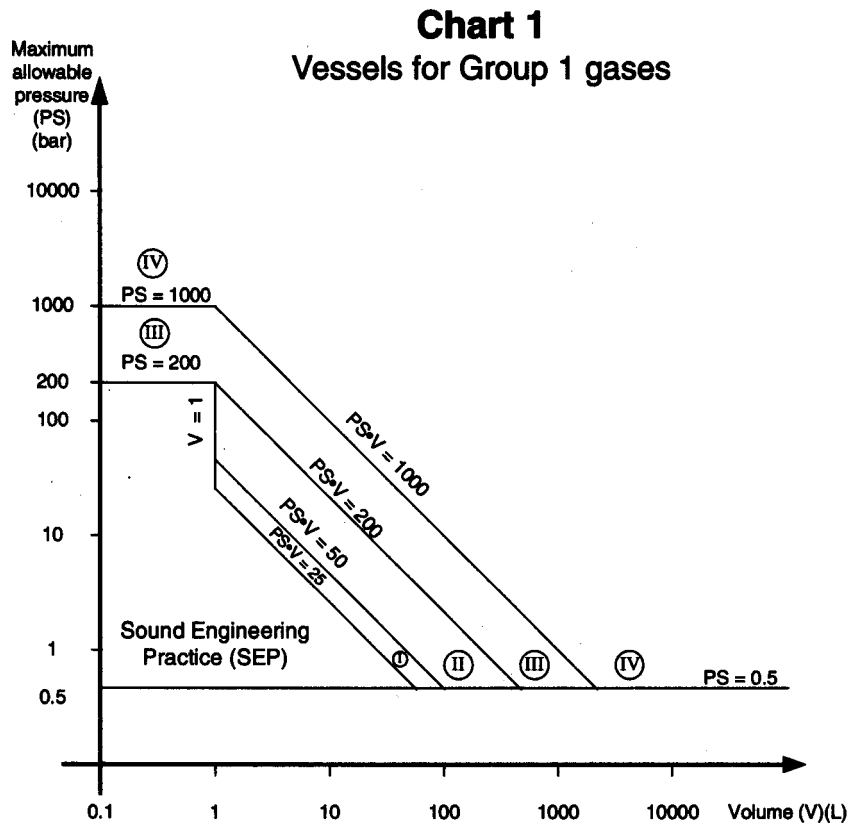
The regulations also states that ‘Other means of ensuring the safe condition of the pressure equipment may be applied where it is too small for physical internal access, where opening the pressure equipment would adversely affect the inside or where the substance contained has been shown not to be harmful to the material from which the pressure equipment is made and no other internal degradation mechanisms are reasonably foreseeable’.

There is also a requirement for ‘instructions for the user’ to be supplied with the pressure equipment. These instructions should contain all the necessary safety information relating to putting the equipment into service, its continued safe use and maintenance. If appropriate, reference should be made to hazards arising from misuse.

The form that the conformity assessment takes is dependent on the classification of the pressure equipment. This classification is based on:

- a) The type of equipment – vessel, piping or steam generator.
- b) The state of the fluid contents – gas or liquid.
- c) The fluid group of the contents – Group 1 (dangerous) or Group 2 (all others including steam).
- d) The maximum allowable pressure.
- e) The volume in litres or the nominal size as appropriate.

With this information the manufacturer can identify the relevant chart and determine the correct classification of the equipment e.g.:



Exceptionally, vessels intended to contain an unstable gas and falling within categories I or II on the basis of Chart 1 must be classified in category III

The relevant category is then taken from these charts. It can be seen, from this example, that the category is proportional to the potential hazard i.e. the higher category numbers relate to the greater risk from the release of stored energy.

The module(s) of conformity assessment are then deduced from the category. The conformity assessment can vary from internal production control by the manufacturer without the involvement of a notified body to the implementation of an approved quality system and a design, manufacturing and documentation review by a notified body.

2.1.3. Management of Health and Safety at Work Regulations 1999

The Management of Health and Safety at Work Regulations (MHSWR) (2.5) requires that all employers 'assess the risks to workers and any others who may be affected by their undertaking' and that they should 'undertake a systematic general examination of their work activity and that they should record the significant findings of that risk assessment'. In essence, the risk assessment guides the judgement of the employer as to the measures needed to fulfil the statutory duties of the Health and Safety at Work Act.

It follows, therefore, that employers with pressure systems on their sites are required to carry out an assessment of the risks associated with that system. With respect to the risks associated with the release of stored energy in-service, the employer will meet his obligations under the MHSWR by complying with the requirements of the PSSR. For all other risks associated with the equipment, the employer should ensure that the risk assessment identifies the measures he needs to take.

The ACoP issued in support of the MHSWR states that the risk assessment should be 'suitable and sufficient'. It should identify the significant risks, enable the employer to identify and prioritise the measures that need to be taken to comply with the relevant provisions. In addition, it needs to be appropriate to the nature of the work and be such that it remains valid for a reasonable time.

The ACoP also discusses the issue of review and revision. The employer is required to review and modify where necessary the risk assessment. The assessment should not be a 'once and for all' activity. The nature of the work (i.e. the operating parameters) may change and that there may be developments that suggest that an assessment may no longer be valid or that it can be improved. It is prudent to plan a review of risk assessments at intervals dependent on the nature of the risks and the degree of likely change.

There are no set rules about how a risk assessment should be undertaken. It is accepted that it will depend on the nature of the undertaking and the type and extent of the hazards and risks. The process should be practical and would not be expected to cover risks which are not considered reasonable foreseeable. For small systems presenting few or simple hazards a suitable and sufficient risk assessment can be based on judgement i.e. a qualitative approach. For larger more complex systems, the assessment may need to be developed into a full safety case incorporating a quantitative approach.

The preventative and protective measures that can be taken following the risk assessment depend upon the requirements of the HSW Act and any other relevant legislation as well as the outcome of the risk assessment. It is always best to avoid the risk altogether, if that is possible, and to treat the risk directly rather than just mitigate for the outcome of the risk.

2.1.4. The Provision of Use at Work Equipment Regulations 1998

As the MHSWR covers the general requirements for risk assessments, the Provision of Use at Work Equipment Regulations (PUWER) does not include a specific regulation requiring a risk assessment (2.6).

Regulation 4 – Suitability of work equipment states that 'Every employer shall ensure that work equipment is so constructed or adapted as to be suitable for the purpose for which it is used or provided and in selecting work equipment, every employer shall have regard to the working condition, and to the risks to the Health and Safety of persons which exist in the premises and any additional risk posed by the use of that work equipment' and the supporting guidance goes on to say that the

risk assessment carried out under Regulation 3 of the MHSWR will help to select work equipment and assess its suitability for particular tasks.

Regulation 6 – Inspection states that ‘Every employer shall ensure that work equipment exposed to conditions causing deterioration which is liable to result in dangerous situations is inspected at suitable intervals to ensure that Health and Safety conditions are maintained and that any deterioration can be detected and remedied in good time’ and again the supporting ACoP and guidance states that a risk assessment carried out under Regulation 3 of the MHSWR will help identify those risks that would benefit from a suitable inspection being carried out.

2.1.5. The Control of Major Accident Hazards Regulations 1999

The Control of Major Accident Hazards Regulations (COMAH) (2.7) requires the preparation of a Major Accident Prevention Policy. This must demonstrate that all measures necessary have been taken to prevent major accidents and limit their consequences to persons and the environment. It recognises that risk cannot always be completely eliminated, but implies proportionality between the risk and the measures taken to control that risk.

Preventing the loss of containment of hazardous substances is often key to preventing major accidents. It is therefore necessary to take appropriate measures to achieve and demonstrate adequate continuing integrity of containment equipment (vessels, tanks, pipework etc). A suitable scheme of in-service examination can therefore be an important part of the measures necessary to prevent major accidents, but is not an explicit requirement of the COMAH regulations.

Where equipment is covered by the requirements of the PSSR and COMAH, the in-service examination under PSSR are considered to be adequate for both sets of regulations. In cases where the PSSR does not apply (e.g. atmospheric storage tanks), the requirement for in-service examinations may be less regulated. It is, however, often convenient to include such equipment in a written scheme of examination.

A Major Accident is defined as ‘an occurrence (including in particular, a major emission, fire or explosion) resulting from uncontrolled developments in the course of the operation of any establishment and leading to serious danger to human health or the environment, immediate or delayed, inside or outside the establishment, and involving one or more dangerous substances.’ The guidance issued in support of the COMAH Regulations also states that ‘The occurrences must have the potential to cause serious danger but it is not necessary for the danger to result in harm or injury. It is the potential that is relevant.’

The guidance to Regulation 4 – General Duty states that ‘the ideal should always be, wherever possible, to avoid a hazard altogether however accident prevention should be based on the principles of reducing risk to a level as low as is reasonably practicable (ALARP).

Any process or activity should be reviewed to see if it can be made inherently safer and to ensure that risks have been reduced as low as is reasonably practicable. Good

practice, as to the action taken to reduce the risk, may include the development of sound operating and maintenance and inspection procedures.

The guidance also recognises that it is not always necessary to adopt the quantified risk assessment approach but suggests that this method may be of help in setting priorities when comparing risk values.

2.2. GUIDELINES ON PERIODICITY OF EXAMINATIONS

Guidelines have been published by various organisations giving advice on what should be good practice when setting the intervals between statutory inspections of pressure equipment. Three of these published guidelines are discussed below.

2.2.1. SAFed - Guidelines on Periodicity of Examinations

The Safety Assessment Federation (SAFed) is an organisation that represents the interests of companies engaged in independent inspection and safety assessment of engineering and manufacturing plant, systems and machinery.

Following the introduction of the PSTGCR in 1989 (2.8), SAFed considered that there was a need for additional, practical guidance on the recommended intervals between successive examinations of pressure systems. Guidance was also needed on the areas to be investigated when considering an extension of existing intervals. Consequently SAFed produced a set of guidelines on the periodicity of examinations (2.9).

The Foreword of the guidelines states that they should only be adopted after proper consideration has been given to the individual circumstances pertaining to each pressure system. Guidance is given on the extending of intervals between examinations including the factors and relevant information that should be considered. Descriptions of the typical failure modes that can occur are provided. The concept followed in these guidelines mirrors the basic qualitative approach to risk assessment as detailed elsewhere in this document.

2.2.2. CEOC - Periodicity of Inspections of Boilers and Pressure Vessels

The European Confederation of Organisations for Testing, Inspecting, Certification and Prevention (CEOC) represents the technical inspection organisations within the European Union (EU). It was recognised that in the countries of the EU the interval between the inspection of a given vessel can vary enormously without any apparent technical justification. It was therefore decided to develop guidelines (2.10) to advise the different bodies.

The first section reports a study that compares the current inspection intervals throughout the member states. This study found that certain countries do not impose any statutory duties on users of pressure systems to have plant examined whereas other countries insist on the same type of plant to be examined every year. It is evident from the examples used that the basis of examination requirements is not one of risk.

CEOC recognises that it would seem technically desirable to carry out plant examinations that follow a variable cycle throughout the life of that plant. During the 'normal' life of the plant after the first examination, the periodicity between inspections could be extended. However, towards the end of the anticipated or design life of the plant the periodicity between inspections should be reduced.

CEOC suggests that plant should be classified into different categories depending on pressure and volume. This recognises the potential consequence of failure due to the sudden release of stored energy. The method adopted then follows the semi-quantitative route, described elsewhere in this document. Prescribes scores to the likelihood of failure, are in turn entered into a 'risk matrix' with the maximum periodicity between inspections being established from the overall level of risk.

2.2.3. Institute of Petroleum - Pressure Vessel Examination

This code is part of the Institute of Petroleum (IP) Model Code of Safe Practice in the Petroleum Industry (2.11). Its purpose is to provide a guide to safe practices in the in-service examination of pressure vessels used in the petroleum and chemical industries. The advice given is based on existing good practices in these industries that have proved necessary and beneficial for the safe and economic operation of pressure equipment.

The code suggests two concepts which interrelate and affect decisions regarding examination intervals:

- a) The allocation of Grades.
- b) Sampling examination procedures.

The allocation of the grading is dependent on an assessment carried out following the first examination. If deterioration is expected at a relatively rapid rate or there is little evidence or knowledge of the operational effects then the plant is allocated a low grade i.e. representing a high risk of failure. If deterioration is at a reasonable and predictable rate then the grading can be less severe.

This again follows the semi-quantitative method for the assessment of risk and recognises the importance of good information. The periodicity between examinations is then set according to the type of vessel and the allocated grading as shown below:

Examination frequency:

Equipment	Grade 0	Grade 1	Grade 2	Grade 3
Process pressure vessels and heat exchangers	36	48	84	144
Pressure storage vessels	60	72	108	144
Protective devices	24	36	72	-

Where a group of vessels are substantially the same in respect to geometry, design, construction and conditions of service, then the IoP consider it reasonable to take a number of the vessels as a representative sample. This can continue provided that

the findings of the examination are acceptable and that each individual vessel is subjected to an examination within the maximum period i.e. 144 months.

The advice provided in the ACoP to the PSSR is different to the above. The ACoP states that it is not permissible to carry out an examination of a sample of a group of identical vessels as representative of the population. This is discussed further in Chapter 7.

2.3. GUIDELINES ON RISK ASSESSMENTS

2.3.1. Health and Safety Executive – A Guide to Risk Assessment Requirements

This guide (2.12), published with a supporting leaflet entitled ‘five steps to risk assessment’, is intended for employers who have duties under Health and Safety law to assess risks in the workplace (see Section 2.1.3). The five steps referred to in the leaflet are:

Step 1 : Look for the hazards.

Step 2 : Decide who might be harmed and how.

Step 3 : Evaluate the risks and decide whether the existing precautions are adequate or whether more should be done.

Step 4 : Record your findings.

Step 5 : Review your assessment and revise it if necessary.

The leaflet is aimed at the commercial, service and light industrial sectors. Although hazards in these sectors may be few and simple, the basic concept is the same. The method of risk evaluation tends to be qualitative, which is sufficient where the hazards are simple and limited.

2.3.2. Health and Safety Executive – Reducing Risks, Protecting People

This publication (2.13) is a discussion document, produced by the HSE, to generate the views of the public and industry with respect to the process involved in the assessment of risk adopted by the HSE. It describes the decision making processes and the factors that influence the final decisions on what risks are unacceptable, tolerable or negligible. In doing so it highlights the difficulties in taking account of ethical, social, economic and scientific considerations.

It also introduces the important concept of tolerability. This refers to the willingness of society to live with a risk with the understanding that the risk is worth taking and that it is being properly controlled and managed.

2.3.3. CEOC – Risk Assessment: A Qualitative and Quantitative Approach

These recommendations (2.14) were produced to unify the experience and methods and co-ordinate the approach of various inspection organisations to safety in the use of plant and machinery. The recommendations are divided into three sections.

- The first deals with determining how a major hazard could arise at an installation.

- The second details how to estimate the probability of a minor accident.
- The third deals with the assessment of consequences of a minor accident.

It is suggested that there are two methods for the estimating of the probability of failure:

- The historical approach.
- The analytical approach.

The historical approach relies on existing data from actual occurrences at similar installations. The calculated accident frequency is then used to establish the probability of an accident at the installation being studied.

The analytical approach relies on statistically based failures, with the failure rates of each component being obtained from data banks. The numerical data are then processed from the first input and proceeding, through the logic flow diagram, using mathematical relationships.

It is acknowledged that both methods have certain weaknesses and the one that is more appropriate for the particular study under consideration should be selected. The historical approach is less time consuming and, providing that sufficient data exists, it is possible to create credible accident scenarios for the plant under examination.

The consequence of an accident depends on a variety of parameters and mathematical models have been developed to simulate certain release situations. Provided the relevant parameters are known it is possible to use these models to estimate the effects of the accident.

The recommendations conclude that ‘Quantitative risk analysis has not yet reached the stage of development where it can be used indiscriminately to appraise risks associated with the process industries. Work should continue on the improvement of both methods used and the data bases required for risk analysis, because it is a potentially useful tool for assisting with safety decision making.’

2.4. GUIDELINES ON RISK BASED INSPECTION

2.4.1. Health and Safety Executive – Risk Based Inspection (RBI)

This internal circular (2.15), issued by the Hazardous Installations Directorate (HID), describes a risk based approach to planned plant inspection. It has the primary function of providing guidance to HSE inspectors for auditing plant inspection systems which adopt RBI. It is a spring board for the development of this guidance on RBI which has the intention of providing more detailed and extensive guidance and supporting information.

2.4.2. ASME – General Document Volume 1 CRTD-Vol.20-1

This document (2.16) gives a general overview of the principles involved in RBI and discusses the methods by which information is gathered and analysed.

A four-part process is recommended to rank or classify systems for inspection and to develop the strategy of that inspection. This process includes:

- a) Definition of the system.
- b) A Qualitative Risk Assessment.
- c) A Quantitative Risk Analysis.
- d) Development of Inspection Programme.

The qualitative risk assessment enables the individual plant items within the system to be prioritised. This initial assessment involves defining the failure modes and causes, identifying the consequences, estimation of risk levels, ranking the subsystems and finally ranking the individual components.

The quantitative risk analysis is then applied to the individual components of the system, the recommendation being that a fully detailed Failure Modes Effects Criticality Analysis (FMECA) should be carried out, this analysis would capture information from the qualitative risk assessment and assign probabilities and consequences of failure for each component. It is also recommended that operating experience databases and analytical models are used to assist in this work although it is recognised that uncertainties will exist in such data and suggestions are provided to take those into account.

The next stage in this process is the development of the inspection programme where the inspection strategies of technique and frequency are evaluated, performed and then the results are assessed to update the state of knowledge for the next inspection.

This document mainly deals with a theoretical approach to the problem, detailing the actual methods of analysis such as FMECA, Structural Reliability and Risk Assessment (SRRA) and Probabilistic Risk Analysis (PRA). There are no examples of the risk assessment and analysis presented, only examples to illustrate the differences between the application of risk management styles to risk based inspection.

2.4.3. API Publication 581 – Base Resource Document: Risk Based Inspection

This is an industry specific document (2.17) designed to be applied to the petroleum and chemical process areas. It follows the same overall approach as the ASME document and recognises that a RBI programme aims to:

- 1) Define and measure the level of risk associated with an item.
- 2) Evaluate safety, environmental and business interruption risks.
- 3) Reduce risk of failure by the effective use of inspection resources.

The level of risk is assessed by following the same procedure as described in the ASME document i.e. a quantitative analysis is generally applied after an initial qualitative analysis has established those plant items for further analysis.

The qualitative approach assesses each plant item with a position in a 5 x 5 risk matrix. The likelihood of failure is determined from the sum of six weighted factors:

- a) Amount of equipment within item.
- b) Damage mechanism.
- c) Usefulness of inspection.
- d) Current equipment condition.
- e) Nature of process.
- f) Safety design and mechanisms.

The consequence of failure is divided into only two factors:

- a) Fire/Explosion.
- b) Toxicity.

The general approach of the quantitative analysis is to first establish details on the process, the equipment and other pertinent information. Risk is then calculated as the product of each consequence and likelihood for each damage scenario, the total risk for an item being the sum of all the scenario risks:

$$\text{risk}_S = C_S \times F_S$$

where:

- S = Scenario
- C_S = Consequence of scenario
- F_S = Failure frequency of scenario

$$\text{Risk}_{\text{ITEM}} = \sum \text{Risk}_S$$

The inspection programme is then developed to reduce that risk. To do that one needs to establish:

- 1) **What** type of damage to look for.
- 2) **Where** to look for damage.
- 3) **How** to look for damage.
- 4) **When** to look for damage.

What and Where is established from reviewing the design data, process data and the equipment history, How to look for the damage is decided by reviewing the damage density and variability, inspection sample validity, sample size, detection capability of method and validity of future prediction based on past observations. When to look for damage is related to the estimated remaining life of the component.

This document prescribes actual methods to use, with specific values that can be applied to given situations and conditions. There are also worked examples to obtain an idea of how to assess a system, what constitutes a failure and how to assess the resulting consequences. There are also several workbooks which can be utilised to assess a plant in terms of both qualitative and quantitative risk analysis. There are references made to known reliability data plus some details of specific reliability data available within the document itself.

2.5. SOFTWARE PACKAGES

There are many commercially produced software packages currently on the market. These can provide the RBI team with a model for the assessment and ranking of risk. Packages vary in complexity but generally follow the semi-quantitative risk assessment methodology.

Appendix E gives some factual information for a sample of five of these packages produced by the following suppliers.

- Akzo Nobel
- Det Norsk Veritas (DNV)
- The Welding Institute (TWI)
- Tischuk
- LMP Technical Services

Inclusion of any package in this list does not indicate that they are endorsed by the authors. None of the methods reviewed have been validated. It is considered that their practical application is limited and they should only be used to guide and supplement the risk assessment and inspection planning process not replace it.

2.6. REFERENCES FROM CHAPTER 2

2.1 The Health and Safety at Work etc Act 1974: 'A Guide to the Health and Safety at Work etc'. Act 1974 4th Edition. 1990 ISBN 0 7176 0441 1.

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2.5 Management of Health and Safety at Work Regulations 1999. Approved Code of Practice and Guidance L21 (Second edition). HSE Books, 2000, ISBN 0 7176 2488 9.

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2.7 The Control of Major Accident Hazards Regulations 1999. Guidance on Regulations L111, HSE Books, 1999, ISBN 0 7176 1604 5.

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2.11 Institute of Petroleum: Pressure Vessel Examination, Model Code of Safe Practice Part 12 Second Edition. The Institute of Petroleum, 1993, ISBN 0 471 93936 6.

2.12 Guide to Risk Assessment Requirements. HSE Books, 1996, ISBN 0 7176 1565 0.

2.13 Reducing Risks, Protecting People. Discussion Document. HSE Books, 1999, DDE11 C150 5/99.

2.14 CEOC - Risk Assessment : A Qualitative and Quantitative Approach. Confédération Européenne d’Organismes de Contrôle. R 35/CEOC/CR1 87 Def.

2.15 Risk Based Inspection (RBI):’ A Risk Based Approach to Planned Plant Inspection’. Health and Safety Executive – Hazardous Installations Division, CC/TECH/SAFETY/8, 26/04/1999.

2.16 Risk Based Inspection – Development of Guidelines, Vol.1 – General Document, The American Society of Mechanical Engineers (ASME), CRTD, Vol.20-1, 1991, ISBN 0 7918 0618 9.

2.17 Risk Based Inspection Base Resource Document, API Publication 581, Preliminary Draft, American Petroleum Institute, May 2000.

3. APPLICATION OF RISK BASED INSPECTION

3.1. SYSTEM DEFINITION

The Pressure Systems Safety Regulations 2000 (PSSR) (3.1) are considered to be goal setting in nature – that is the required goal is stated but how that goal is achieved is not prescribed. The PSSR define what constitutes a pressure system but do not delineate the boundaries between separate systems. This is left to the Duty Holder and the Competent Person to decide.

Many different criteria are used throughout industry to define the boundaries between pressure systems. It may be convenient for the boundaries of a system to be defined as the walls of a particular building or from one particular isolating valve to another. Systems may also be defined by the process conditions or the process fluids.

There is a risk in defining a system too widely. The complete picture of safety and integrity can be clouded by too much information and this may result in confusion and misinterpretation. On the other hand, too narrow a definition may lose sight of the impact a failure or process upset in one subsystem may have on another. Breaking down systems into manageable and meaningful subsystems allows both the Duty Holder and Competent Person to concentrate on specific issues relating to that subsystem i.e. a particular relevant fluid or damage mechanism.

It is therefore of importance, before any programme of risk based inspection is established, that the extent of each system is clearly defined. An inventory of individual items of equipment within each system is then developed. The inventory needs to be comprehensive and include all items that might relate to a failure of the system.

The PSSR are only concerned with the release of stored energy. Apart from the scalding effect of steam, the regulations do not address issues relating to the toxic or flammable nature of the fluid within the system. As a result it is possible that items crucial to the validity of risk assessment and safety are not identified under the PSSR.

These items could include plant such as static storage tanks, pressure relief streams, pipework supports, pumping equipment, process measuring devices etc. They should be included within the inventory of plant even if some are to be discounted at a later stage of the assessment process.

The Duty Holder will gather and review all available data relating to each system. This review allows an initial screening process to identify those systems that will be the focus of the risk assessment. Interrelationships and dependencies of systems can be established at this stage. Techniques for doing this are discussed in Chapters 5 and 6.

3.2. CRITERIA FOR APPLICATION

Good safety management and a plant-wide understanding of safety by the Duty Holder are pre-requisites to adopting a risk based approach. Plant integrity management and inspection of any system can then be based on an assessment of the risk of failure. A risk based approach can also be introduced into other aspects of plant management, such as operation and maintenance strategies.

Sufficient information is an essential requirement for risk to be assessed. The introduction of the Pressure Systems and Transportable Gas Containers Regulations (PSTGCR) in 1989 (3.2) has assisted Duty Holders to obtain the necessary information for a risk based approach. Relevant regulations are:

- Regulation 5 – Provision of information and marking,
- Regulation 7 – Safe operating limits,
- Regulation 11 – Operation,
- Regulation 12 – Maintenance,
- Regulation 13 – Modification and repair,
- Regulation 14 – Keeping of records.

There have, however, been many cases where Duty Holders have lacked information on:

- The design, materials, construction or history of their plant,
- The actual operating conditions of their plant,
- The effect that operating conditions have on the safety and integrity of that plant,
- The predicted condition of the plant from previous inspections.

The reasons for lack of information are many fold but have known to include such aspects as loss or non-supply of initial data, a lack of basic engineering knowledge, a lack of process/operational knowledge, or just an inability to make themselves aware of the facts.

Before the PSTGCR were issued in 1989, it had not been necessary to subject some pressure plant to any routine, periodic, or documented inspection since its installation. (This was only required for boilers and steam/air receivers under the 1961 Factory Act.) Specific knowledge of the manufacturing inspections and construction concessions was not needed. Therefore, for some older or second hand plant or equipment, a full service history does not exist. All this makes risk based inspection difficult to apply.

In order to apply risk based inspection where there is a lack of service or inspection history, it is first necessary to undertake a comprehensive benchmark inspection. The results obtained from the benchmark inspection would then be fed into the risk assessment process so that future inspections can be planned on the basis of firm knowledge of the current condition.

The introduction of the Pressure Equipment Regulations (PER) in 1999 (3.3), allows manufacturers to construct certain pressure plant without any specific design or constructional verification by a third party. This may raise issues with respect to the quality of the information relevant to integrity of new equipment. Duty Holders and Competent Persons will need to take this into account when formulating a risk based in-service inspection strategy for CE marked equipment under the PER.

Where there is doubt about the effectiveness or performance of previous inspections, such that the condition of the equipment inspected is uncertain, risk based inspection is difficult to apply. RBI must be able to address all relevant factors have to be taken into account in specifying the inspection strategy. These factors will vary depending on the type and complexity of the system and it is likely that they would vary between individual items within the system. By careful consideration of the way the system operates and the processes used, the relevant factors can be identified.

It should be recognised that the ‘inspection strategy’ encompasses:

- The type of the inspection, e.g. full internal, non-invasive, continuous monitoring.
- The nature of the inspection techniques applied, e.g. visual, non-destructive testing (NDT), or metallurgical analysis.
- The scope of the inspection, i.e. the specific material targeted.
- The inspection interval.

The resulting inspection strategy from a RBI assessment would be a combination of those aspects considered to be the most safe yet cost effective. The development of the inspection strategy is discussed in more detail in Chapter 8.

A number of other potential limitations in the application of the RBI approach include:

- Reliance on the Duty Holder for accuracy of operational parameters.
- Lack of experience in identifying relevant failure modes and damage mechanisms.
- Reliability and accuracy of the available inspection technique.
- Lack of construction and usage history.
- The possibility of the unexpected failure.

To avoid these issues it is of the utmost importance that the RBI team should be composed of individuals having the necessary competence and knowledge of all aspects of the plant.

3.3. DRIVERS TOWARDS RBI

The reasons or drivers for Duty Holders to adopt a risk based approach to the management of their plant can be varied. It is generally agreed that one of the main drivers is to optimise the costs of complying with statutory obligations for Health and Safety. The main aim and benefit of RBI, when properly carried out, must always be to manage the likelihood and consequences of plant failure at an acceptable level and thereby avoid unreasonable risks of harm to people and the environment.

Failures almost always have a direct or indirect affect that is harmful to the business of the Duty Holder. For example:

- Lost production,
- Costs of follow-up to an incident, replacement of equipment etc,
- Loss of any public image the user may have established within the community,
- Higher insurance premiums,
- Costs of legal action.

Different consequences arise from plant failure with different types of risk. Duty Holders may consider potential financial consequences as well as Health and Safety issues. The RBI team should ensure that financial considerations and broader company concerns do not distort or reduce the importance of the safety of personnel. In well managed businesses they are indistinguishable.

An example of this would be where a Duty Holder of ten items of equipment identifies that eight of those items are considered a low risk with respect to Health and Safety with the remaining two being considered a medium risk. However, when considering loss of production, six of those eight low Health and Safety risk items were in a high financial risk category. The RBI team should ensure that the attention, resource and scrutiny that those six items will receive does not compromise inspection of the two medium Health and Safety risk items. This example clearly shows that there is a need to ensure balance within the RBI team with respect to the possible differing interests.

Inspection bodies and Duty Holders have traditionally followed a prescriptive inspection philosophy. This has often been criticised for causing excessive plant downtime leading to unnecessary loss of production and operating revenue. In addition, inspection can have the potential for the plant returning to service in a less safe condition.

For example, some equipment only suffers degradation as a result of being opened up for a visual examination. For other plant, the most onerous condition is that experienced at either start-up or shut-down. In these cases, there are strong arguments for inspection being carried out less often or non-intrusively.

Equipment is not only shut down for inspection but also for maintenance purposes. These may be driven by process or energy efficiency requirements. For example, removal and replenishment of catalysts and fouling of process plant. Plant operators

are seeking to increase the flexibility of the inspection scheduling to allow plant shutdowns to be governed only by the need for maintenance.

3.4. SUMMARY OF MAIN POINTS

- (a) Every pressure system or container of hazardous materials must be clearly defined.
- (b) The boundaries and limits of the system must be clearly defined.
- (c) An inventory of all items of pressure or containing equipment within the system should be developed.
- (d) This inventory should include any non-statutory items of plant equipment relevant to the risk of failure of the system.
- (e) Full account should be taken of any lack of relevant information.
- (f) When assessing the current condition, the RBI team should be able to demonstrate that all relevant factors have been taken into account in specifying the inspection techniques.
- (g) The limits to the effectiveness and performance of the inspection techniques and the quality of data from previous inspections should be clearly understood.
- (h) The reasons/drivers for adopting RBI should be clearly defined and consistent with good Health and Safety management.
- (i) Maintenance requirements should be in place and they should not be in conflict with the inspection plan.

3.5. REFERENCES FROM CHAPTER 3

3.1 Pressure Systems Safety Regulations 2000 (SI 2000 No. 128): 'Safety of pressure systems'. Approved Code of Practice L122. HSE Books, 2000, ISBN 0 7176 1767 X.

3.2 Pressure Systems and Transportable Gas Containers Regulations 1989. Guidance on Regulations HS(R) 30, HMSO Publications, 1990, ISBN 0 11 885516 6.

3.3 Pressure Equipment Regulations 1999 (SI 1999/2001): 'Pressure Equipment'. Guidance notes on the UK Regulations URN 99/1147, DTI, November 1999.

4. THE RBI TEAM

4.1. COMPOSITION AND COMPETENCIES

In all but the simplest situations, risk analysis and inspection planning require a range of technical inputs and perspectives from different disciplines. Risk based inspection (RBI) is therefore best undertaken by a team. The first step is to determine the requirements of the team and to identify its members.

The team needs to have a team leader with the authority to manage the team and the responsibility of ensuring that an appropriate RBI plan is developed. For pressure systems and other regulated equipment, the Competent Person will normally be part of the team in order to fulfil statutory responsibilities. The number in the team and its composition will vary depending on the complexity of the installation, (although three might be a minimum), but the team should be able to demonstrate adequate technical knowledge and experience in the following areas:

- Risk assessment.
- Production process hazards and the consequences of failure.
- Plant safety and integrity management.
- Mechanical engineering including materials chemistry and plant design.
- Plant specific operation, maintenance and inspection history.
- Inspection methods and the effectiveness of NDE techniques and procedures.

It is desirable that there exists a breadth of knowledge and experience from work on other plants and other sites. The Competent Person and independent parties are useful in this respect. Sometimes, particular specialists (e.g. corrosion chemist, dispersion analyst, statistician) may need to be consulted.

Where there are significant Health and Safety implications arising from equipment failure, the qualifications and competence of the individuals in the team needs to be of a professionally recognised standing. Duty Holders must be able to demonstrate that they have the necessary technical expertise within their RBI team. Where such expertise is not available in-house, or through the Competent Person, Duty Holders should take advice from appropriate external experts and consultants.

The RBI team should contain someone having responsibility for safety management in relation to the site management and environment. This can enable identification of the wider consequences of equipment failure and suitable mitigating measures. As inspection forms part of the overall safety management process, the RBI team is expected to have reporting links and the ability to feedback information and concerns to other safety bodies.

4.2. ROLE OF THE COMPETENT PERSON

Within the Pressure Systems Safety Regulations 2000 (PSSR), the ‘Competent Person’ is used in connection with three distinct functions. Different individuals may carry out these functions. They are:

- To assist the Duty Holder on the scope of the scheme of examinations.
- To draw up or certify the suitability of the written scheme of examination.
- To carry out or take responsibility for the examination and approve the report.

In practice, Duty Holders and regulatory authorities rely to a great extent on the independence and breadth of technical knowledge and experience of the Competent Person. Within RBI the Competent Person has an important role in ensuring an appropriate balance of risk in written schemes of examination. The Competent Person is also responsible for ensuring that examinations are carried out with the required effectiveness and reliability.

The regulations require that the Competent Person, when carrying out his/her duties, is sufficiently independent from the operating functions of the company to ensure adequate segregation of accountabilities. This becomes particularly important when non-prescriptive examination schemes are developed since there is more reliance on the judgement of the individuals involved. Decisions about inspection to ensure the safety of equipment should be separated from decisions on the economics of production.

The wider and more detailed considerations of the risk assessment place increased demands on the expertise and experience of the Competent Person. A good knowledge of the causes and frequency of equipment failures together with an appreciation of hazards and accident scenarios is required. Many Competent Person organisations are already well equipped for this role as insurers of engineering risks.

Wider industrial experience is important since the perception of the risks of failure tends to be a relative rather than an absolute judgement. In RBI, the Competent Person may need to rely on expertise and experience available within his/her organisations. Good access and communication between the Competent Persons and their technical support staff is required.

4.3. ROLE OF THE TEAM LEADER

The Duty Holder is responsible for ensuring that the team leader develops an inspection plan that adequately addresses the risks to Health and Safety. The team leader must therefore separate the risks to Health and Safety from the risks to production. It is therefore highly desirable that the team leader is and is seen to be organisationally independent from the direct pressures of the production function.

As RBI involves risk analysis, some Duty Holders will appoint a team leader from their engineering, technical or safety functions. Under some circumstances, the Duty Holder may appoint a team leader from an external organisation if there is insufficient expertise in-house. Close co-operation with the advisory and certifying roles of the Competent Person is expected, and some Duty Holders may choose the Competent Person to lead the RBI team.

The team leader should be able to call upon other staff and experts as required and be able to command sufficient resources for the RBI process to operate effectively. For major installations, the team leader needs to have sufficient seniority as the risk

assessment and inspection may affect several parts of the organisation. Authority to obtain the information needed for the risk assessment is required.

It is beneficial if the team leader has knowledge of risk assessment so as to be able to control the process and make the appropriate judgements. Wider experience of industrial risks and practices can help the team leader maintain an appropriate balance between conflicting factors. The team leader must have sufficient all round technical knowledge and experience of plant to know what information is required and where to find it.

4.4. RIGOR AND CONDUCT OF THE APPROACH TO RBI ASSESSMENT

Before the process of RBI can commence, the team must know its terms of reference and the necessary rigor of the approach. In some situations, the RBI team will have formal terms of reference from senior management stating the purpose and objectives of the inspection planning process. In many cases, the objectives of the process are simply to design an inspection plan that clearly addresses the risks to Health and Safety whilst meeting the relevant regulations.

It is helpful for Duty Holders to indicate ways in which the value of inspection can be measured. Indicators might include the reduction of uncertainty, the numbers of service failures, or the improved management of degradation within the design allowances. This could also highlight the risks from not inspecting and time dependent factors.

As risk assessment is best undertaken as an interactive process, the team needs to have a number of meetings at different stages. It is usual for a record of these meetings to be taken for future reference and as an audit trail. The record should note how qualitative judgements and decisions were reached, and cite appropriate references to other documentation.

The choice and rigor of the approach should reflect the complexity of the installation and processes, the potential hazards, and the consequences of failure. These will influence the need for detailed technical analyses or where more reliance can be placed on engineering judgement and experience. Situations requiring a more rigorous approach will include those where there can be high consequences resulting from a single component failure, or where there are complex plant conditions and active degradation mechanisms.

Before starting the process, a wise team will assess the circumstances and the chances of a successful move towards a risk based framework. This will depend on the availability and reliability of the information required and how much is currently unknown. Timescales, costs and the access to sufficient expertise may also be limiting factors.

Qualitative approaches to risk assessment can be acceptable and very beneficial. Here engineering judgements are made about the likelihood and consequences of failure on the basis of a systematic assessment of the relevant factors. In many cases, the information required for a quantified risk assessment either does not exist,

or is not sufficiently accurate, to allow this approach to be made with any confidence.

External experts and consultants can contribute valuable technical knowledge and experience, and also provide a useful degree of independence and objectivity in assessing the risks and the adequacy of the inspections proposed. Expert elicitations are a good way of obtaining independent advice and are best carried out when the initial risk assessment and inspection planning are complete. The overall balance of the risks and the value of proposed inspections may be reviewed and adjustments made as necessary.

4.5. SUMMARY OF MAIN POINTS

- a) Risk based inspection is best undertaken by a team.
- b) The number of individuals and composition of the team depend on the complexity of the installation, but a team should have adequate technical knowledge and breadth of experience in the key areas.
- c) Where there are significant Health and Safety implications arising from equipment failure, the qualifications and competence of the individuals in the team needs to be of a professionally recognised standing.
- d) The RBI team is expected to have reporting links and the ability to feedback information and concerns to other safety bodies.
- e) The Competent Person has an important role in ensuring an appropriate balance of risk in written schemes of examination. Good access between the Competent Person and their technical support staff is required.
- f) It is highly desirable that the team leader is, and is seen to be, organisationally independent from the direct pressures of the production function. Team leaders should have the necessary seniority and authority.
- g) The RBI team must know its terms of reference and the necessary rigor of its approach. Records of team meetings should be made, and in particular, note how qualitative judgements and decisions were reached.
- h) Qualitative approaches to risk assessment can be acceptable and very beneficial. In many cases, the information required for a quantitative risk assessment either does not exist, or is not sufficiently accurate.

5. PLANT DATA REQUIREMENTS

5.1. ESSENTIAL DATA

A reliable assessment of the risk requires the Duty Holder to have and maintain an adequate dossier of essential data relating to the plant. This essential data provides the RBI team with a basis on which to judge the continued safe operation. If accurate or complete records have not been maintained, then the assessment will inevitably become conservative which could indicate the risks to be higher than if more information were available. Chapter 9 discusses this issue in greater depth and should be referred to for more guidance.

The essential data will vary from plant item to plant item. The RBI team carrying out the assessment will need to decide which factors are relevant and which can be discounted in each case. One important aspect in the use of such data is that, wherever possible, all data should be validated. It is best to treat hearsay, assumptions or unconfirmed data with caution and make due allowances for uncertainty in the risk assessment.

5.1.1. Original Design and Construction Data

The original design and construction drawings and inspection reports of equipment are essential in order to assess many aspects relating to its structural integrity. This information can be treated as a 'fingerprint' against which the results of all subsequent inspections can be compared. For example, if a vessel is considered liable to corrode and the initial thickness of the vessel is not known, then the corrosion rate cannot be calculated with any degree of accuracy.

The initial quality of materials and fabrication can be determined if data from manufacturing inspections are available. Records of poor material, welding, defects, weld repairs and manufacturing concessions are particularly useful since these can often locate sites of further deterioration in service. Without this information there is uncertainty that may only be remedied by in-service inspection.

Knowledge of the use of NDT and the involvement of a third party inspection body during manufacture, can give a high degree of confidence in the quality of workmanship and conformance with design. The Pressure Equipment Regulations 1999 (PER) (5.1) allow manufacturers to design and construct certain pressure vessels without any third party verification, or surveillance, providing that they operate in accordance with a suitable quality assurance procedure. The Competent Person will take these factors into account when assessing the risks and acceptability of written schemes of examination.

Where it is known that pressure vessels operate under conditions outside their original design specification, a retrospective design assessment is required. Instances include vessels subject to mechanical or thermal fatigue cycles, or high or low temperatures, for which they were not originally designed. The value of a retrospective assessment can only be as good as the supporting data. Without a retrospective design assessment addressing the specific conditions, or where the

supporting data is uncertain or invalidated, it is best to treat such vessels as having a potentially high likelihood of failure, and therefore to subject them to regular inspection.

If all the operating conditions are assessed and taken into account at the design stage, then confidence in initial vessel integrity is increased. Further assurance can be obtained if calculations are carried out during service to confirm the suitability of such vessels using actual service data. Establishing the validity of the service data used is crucial and if uncertainty exists, then worst case' data should be assumed to obtain a conservative result.

5.1.2. Previous Inspection Reports

Previous inspection reports enable trends in the deterioration of equipment to be established. Trends can then be extrapolated for the assessment of the limits to continued safe operation. It is important that all previous inspection reports are considered and not only the most recent.

Many risk based inspection strategies consisting of a review of the inspection frequency, are based only on previous inspection reports. This is not good practice. Whilst previous inspection reports may give an early indication to the possibility of extending the period between inspections, other factors need to be taken into account as part of the assessment process.

The scope and technique of the previous inspections should be taken into account. If those aspects do not match the identified failure modes etc. then great caution should be placed on the validity of such results. Chapter 8 discusses the limitations of the many different NDT techniques that are available in more detail.

By way of example, it could be that a surface crack detection technique such as Magnetic Particle Inspection (MPI) is used when the expected failure mode is sub-surface. Alternatively, where ultrasonic flaw detection is used, the direction of scan of the suspect area may not match the orientation of an expected defect. The problem may not even be that the incorrect technique has been used. It may be that it is expected that the defect will be evident on the external surface of a vessel where only the internal surface is inspected due to the external surface not being accessible due to the presence of lagging etc.

The current condition of the plant should be ascertained and compared to that predicted in the review. If these agree then confidence in the prediction is enhanced. If the actual condition of the plant is below that expected then the review should be re-assessed.

5.1.3. Modifications/Repairs

Documentation associated with any plant repairs or modifications should be reviewed to ensure that the work has been carried out satisfactorily and in accordance with relevant standards etc. The reasons for the repair or modification should also be reviewed to ascertain the effect on probability of failure.

If the need for repair or modification was due to unexpected in-service degradation or abnormal operating conditions, then the assessment team need to be aware of this.

Experience has shown that often very little information, with respect to the reasons or the standard of this type of work, is maintained and the existence of such remedial work may only be highlighted as a result of inspection reports. Should that be the case then a thorough investigation should be carried out, by all parties, in an attempt to resolve the issues associated with such work.

5.1.4. Operation Records/Procedures

The past operating records should be reviewed to ascertain that the plant has been operated satisfactorily and within the stated safe operating limits. It is common for process plant to be continually monitored with regular logging of the operating conditions. All upset conditions should be assessed as to whether they may lead to a possible increase in plant deterioration.

It is considered good practice for operating procedures to be in place, these procedures should include detailed instructions and guidance for the plant to be operated safely during normal running, start-up, and shutdown situations. Procedures should also be in place for emergency shutdown of the plant.

The safe operating limits should not be exceeded, and protective devices should prevent any such condition occurring. If, however, the plant operates under a condition for which it was never designed for then the safe operating limits should be reviewed, recalculated and reassessed where necessary. Problems identified during operation should be logged separately and assessed for their impact on the safety of the system.

Any future proposed changes in plant operation should also be taken into account, with the implication to the continued safe operation of the plant being assessed.

Certain types of plant operate under what is known as 'Time Dependant Conditions' i.e. fatigue or creep, and is designed for a specific life period quoted in either number of cycles for a fatigue condition or number of hours run for a creep condition. The importance of maintaining an operating log becomes more apparent in these situations, as the plant moves closer to the original design life then the amount, level and scope of any inspection will change.

Experience with many users, especially in the chemical process industry where there maybe a Process Engineer as well as a Plant Engineer who both view a plant item from a different aspect and therefore may not always be aware of the loadings, etc. that the individual plant items are being subjected to. Many operating conditions are overlooked purely because they are not being monitored. If the outlet steam temperature of a superheater outlet header is not being measured then the user maybe unaware of the potential of failure due to creep.

5.1.5. Maintenance Records/Procedures

Maintenance is required under the Pressure Systems Safety Regulations 2000 (PSSR) to ensure the safe operation and condition of the plant. A suitable maintenance system should take into account such plant related issues as the age of the plant, the operating/process conditions, the working environment etc. and would be expected to cover issues such as correct operation of safety related devices.

5.1.6. Training and Experience of Supervision

The provision of training to staff responsible for the operation and maintenance of the plant is a requirement under the Provision and Use of Work Equipment Regulations 1998 (PUWER) (5.3). The user would be expected to demonstrate that persons carrying out functions with respect to the safe operation and maintenance of the plant are considered competent in doing so.

5.1.7. Protective Devices

The type and condition of protective devices should be reviewed to establish their suitability under a RBI regime. Protective devices can present particular problems as they usually operate infrequently, or may never operate at all, they may be susceptible to the external environmental conditions or be affected by the contents of the system.

Some devices such as spring loaded pressure relief valves can have their set point verified by testing, either in-situ or removed and bench tested, but others are once-only devices such as bursting discs and buckling pins. This poses a problem to the RBI assessment team who may need to rely on actual plant experience and manufacturers recommendations.

It is considered to be best practice that, as part of the continuing feedback to the RBI assessment (see Chapter 9), all protective devices are tested in the 'as removed' condition. i.e. a safety valve should be tested prior to being cleaned and overhauled.

5.1.8. Installation

Plant that is poorly installed may give rise to premature failure of an item of plant. For example, a section of pipework is not installed correctly, with the result that a nozzle on a vessel is subjected to high direct loadings, then the high stresses could lead to failure at the nozzle/shell junction.

5.1.9. Service Conditions

Various other aspects of design can influence the outcome of the RBI assessment. These include the external environment, the nature of the contents, the facilities for plant entry, the facilities for on-line monitoring or interim inspections, and the age of the plant.

5.2. FAILURE CONSEQUENCES ASSESSMENT

The need for inspection is determined, in the first instance, where a defect may give rise to danger with adverse consequences from failure. The frequency and nature of inspection is subsequently determined by the assessed probability of failure. Thus, a RBI strategy requires knowledge of both the consequences and probability of failure.

When looking at risk reduction of plant during service, it is largely impractical to reduce the consequence of failure except by exclusion of personnel from the area of potential failure.

Typically there are three criteria that can be considered when assessing the consequence of failure:

5.2.1. Health and Safety of Personnel

The location of the plant with respect to on or off-site personnel is a key issue to be taken into account and this will have a significant effect on the consequence of failure. The RBI team should take into account all possible manifestations of failure.

A significant number of fatalities can be caused, if the immediate surrounding area is heavily populated, by the sudden release of stored energy or a boiling liquid expanding vapour explosion (BLEVE) where a vessel containing a flammable liquid under pressure bursts releasing its contents with explosive force. If the contents of the system are toxic then the resulting vapour cloud may cause a significant number of fatalities in heavily populated areas at greater distances from the plant.

Evacuation procedures should be in place where necessary, and, although designed to mitigate the failure rather than prevent the failure, should be taken into account when assessing the likely consequences. Chapter 7 discusses failure mitigation techniques that can be adopted, providing they are relevant to the consequence and nature of the failure. Mitigation of failure must take into account the 'knock on' effects on other items of plant either within the same system, or local to the item in question. There are many ways that a failure can be mitigated such as exclusion of personnel, provision of blast walls, or on-site emergency services but these should be relevant to the nature of the failure.

5.2.2. Environmental Harm

As the public become more aware of the environment and related issues, then this consequence has greater significance. The quantity and toxicity of the contents along with the nature of release should all be taken into account.

Many sites have drainage or spillage systems that prevent the loss of liquids by seeping into the ground preventing possible contamination of ground water etc.

5.2.3. Financial Exposure

Virtually any failure will present the user with a financial consequence. For example, loss of surrounding plant as a result of release of stored energy or the dam burst effect of a large quantity of contents.

Financial exposure can take the form of the cost of providing standby plant, the cost of repairing or replacing damaged equipment, the cost of insurance premiums and the loss of production.

5.3. PUBLISHED DATA, EXPERIENCE AND TECHNICAL GUIDANCE

Safety literature provides valuable information on hazards and control measures, as well as dealing with compliance requirements and issues. It would be beneficial if any reference made to a published document is identified in the final risk assessment report.

Sources of Health and Safety information can include the following:

- Acts and Regulations. These can be difficult to interpret due to use of legal terminology etc. With the introduction of more and more ‘goal setting’ legislation, there can be issues related to interpretation.
- HSC Approved Codes of Practice (ACoP) and HSE Guidance Notes. These documents provide details of what is usually considered to be good practice. The ACoP to the PSSR provides clear and comprehensive guidance on how to comply with the regulations. In some cases they may contain interpretations and non-statutory guidance.
- Published Statistical Databases. These can provide an invaluable insight into likely hazards. The validity and significance of the data should, however, be treated with caution. The HSE are a recognised source of failure statistics. The Smith and Warwick report ‘A survey of defects in pressure vessels in the UK for the period 1962-1978 and its relevance to nuclear pressure vessels’ published in 1983 provides useful information.
- British and International standards. These can provide a valuable source of Health and Safety information.
- Manufacturers or Suppliers Information. This is essential material for identifying the hazards and controls for a particular process or equipment.
- Bulletins from Professional and Trade Organisations. Many user or industry organisations have developed their own codes of practice or guidance notes (e.g. EEMUA and Safety Assessment Federation (SAFed)).
- Text books and Journals. There is a wealth of information to be found in this type of document. Due to the large amount of information and source documentation the subject search process may be prohibitive.

- Accident Databases. Many user organisations such as the Institute of Chemical Engineers and SAFed have produced failure statistics from their own members. However, some of this information may not be in the public domain and so may be difficult to access.
- Internet. Some of the above information is now available on-line.

The experience of the RBI assessment team should be taken into account especially if the team is made up of third party organisations that would bring a depth of knowledge to the process. The use of information gathered should be treated with caution however as, in reality, two identically designed plants will rarely be constructed, operated, or maintained in an identical manner.

5.4. SUMMARY OF MAIN POINTS

- (a) The Duty Holder should make available all essential data for the risk assessment to be carried out.
- (b) The depth of data should be sufficient for the assessment to be carried out.
- (c) The data should be validated.
- (d) Allowances should be made for any assumptions made during the assessment.
- (e) A ‘fingerprint’ of the item should be established.
- (f) The operating parameters should be clearly understood.
- (g) All relevant failure consequences should be considered.
- (h) Environmental or financial issues should not compromise the Health and Safety of personnel.
- (i) Relevant published data should be referred to during the assessment.

5.5. REFERENCES FROM CHAPTER 5

5.1 Pressure Equipment Regulations 1999 (SI 1999/2001): ‘Pressure Equipment’. Guidance Notes on the UK Regulations URN 99/1147, DTI, November 1999 X.

5.2 Pressure Systems Safety Regulations 2000 (SI 2000 No. 128): “‘Safety of pressure systems’. Approved Code of Practice L122, HSE Books, 2000, ISBN 0 7176 1767.

5.3 The Provision and Use of Work Equipment Regulations 1998. Approved Code of Practice and Guidance L22 (Second edition). HSE Books, 1998, ISBN 0 7176 1626 6.

6. RISK ANALYSIS PROCEDURES

6.1. ELEMENTS OF THE PROCESS

Risk based inspection requires the Duty Holder to undertake a risk analysis for the systems and equipment under consideration. The form of this analysis can vary considerably, depending on circumstances, ranging from descriptive qualitative approaches to numerical quantitative approaches. In all approaches, however, the risk analysis should contain the following stages:

- Identification of accident scenarios involving failure of the equipment
- Identification of potential deterioration mechanisms and modes of failure
- Assessment of the probability of failure from each mechanism/mode
- Assessment of the consequences resulting from equipment failure
- Determination of the risks from equipment failure
- Risk ranking and categorisation

Whatever approach is adopted, the risk analysis needs to be complete, systematic and thorough. Duty Holders should ask themselves:

- Have all the stages been addressed for all the equipment under consideration?
- Has a uniform approach been applied throughout the analysis of all items?
- Have all the accident scenarios been identified and analysed in sufficient detail?

Risk analysis may be applied at different levels of detail. Some industrial risk analyses, such as those for complex chemical plant, are sometimes very sophisticated and consider a wide range of accident scenarios resulting from many different initiating events. In risk analyses of simple systems, such as industrial boilers, the range of hazards and consequences is more limited and easier to identify.

It is the legal duty of every employer to perform an assessment of the Health and Safety risks arising as a result of their undertaking. The relevant requirement is in the Management of Health and Safety at Work Regulations 1992, Regulation 3(1) (6.1). ‘Every employer shall make a suitable and sufficient assessment of:

- (a) The risks to the Health and Safety of his employees to which they are exposed at work; and
- (b) The risks to the Health and Safety of persons not in his employment arising out of, or in connection with, the conduct by him of his undertaking’.

Employers and individuals with pressure systems and hazardous materials at their premises should, therefore, have a risk analysis as part of the risk assessment required under the Health and Safety at Work Regulations.

Risk based inspection requires a particular form of risk analysis. This should focus on the dangers of equipment failure resulting from deterioration that could be

detected by periodic examination. Duty Holders should bear in mind that the primary purposes of the risk analysis within RBI are:

- To identify equipment where a defect could give rise to danger.
- To determine the scope of the written scheme of examination.
- To specify equipment for examination under the written scheme.
- To identify the mechanisms and rates of deterioration.
- To set inspection intervals for the first and subsequent examinations.
- To select the most appropriate inspection technique.

6.1.1. Approaches to Risk Analysis

Duty Holders may describe their approach to risk analysis as:

- Qualitative
- Semi-quantitative
- Fully quantitative

These terms should be understood as follows.

Qualitative risk analysis is based primarily on engineering judgements made by the informed personnel and relevant experts in the RBI team. The likelihood and consequences of failure (LOF, COF) are expressed descriptively and in relative terms (e.g. very unlikely, possible, reasonably probable and probable for LOF, high, moderate, low for COF). For qualitative analysis to be used consistently, criteria for the descriptive categories of likelihood and consequence of failure should be defined.

The qualitative approach is an ordered and prescribed process where judgements should reflect the consensus opinion of the team. It is assisted if a standard procedure is followed for each item. Risks within a qualitative approach are usually presented within in a risk matrix as combinations of the likelihood and consequences.

Semi-quantitative risk analysis determines single numerical values for the probability of failure and the consequences from every cause and effect. These values may be obtained from experience, generic failure data, work-books of questions with weighted answers, engineering judgement, or as a result of numerical analysis. The analysis of accident scenarios should generally be more numerically based and detailed than the qualitative approach, but may still contain a large element of engineering judgement.

In a fully quantitative risk analysis, the likelihood and consequences of equipment failure are determined for each accident scenario from the underlying distributions of the variables using reliability analysis methods (6.2). The total probability of failure is evaluated using methods such as survival statistics. The consequences of each accident scenario are analysed in detail, and probabilistic risk assessments used to determine the probabilities of various consequences on a global scale.

In quantitative analysis, risks are evaluated taking account of all the probabilities, and are normally presented on logarithmic probability-consequence plots.

Whilst all these approaches to risk analysis are valid, it is important that there is a high degree of transparency to the process and the data. This may restrict the use of non-validated computer software. The risk analysis process must be capable of being independently assessed.

6.2. IDENTIFICATION OF ACCIDENT SCENARIOS

An accident scenario within RBI is a set of circumstances that involves deterioration of equipment, with the possibility of failure and subsequent events leading to wider detrimental effects and consequences. For example:

- Circumstances could be the susceptibility of materials to corrosion, cyclic loading causing fatigue, failure in water chemistry control, or the potential for damage from impacts or poor maintenance.
- Subsequent events could include fire, explosion, or the release of steam or dangerous gases.
- Detrimental effects and consequences could include effects on the Health and Safety of employees and the public, the environment, and the economics of lost production, equipment and company reputation.

There are many techniques available for Duty Holders to use to identify accident scenarios (6.3). They differ in the degree of detail to which events leading up to and after the failure are identified and quantified within a logical structure. The following lists the main specialist techniques that may be used:

- Hazards and Operability Study (HAZOPS)
- Failure Modes and Effects Analysis (FMEA)
- Fault Tree Analysis (FTA)
- Event Tree Analysis (ETA)
- Human Reliability Analysis (HRA)

Appendix C gives a description of each of these techniques.

6.3. IDENTIFICATION OF DETERIORATION AND MODES OF FAILURE

The process used for identifying deterioration mechanisms for pressure systems and other systems containing hazardous materials should be conducted in a wide ranging and systematic manner. It is more effective if it involves experienced staff from different disciplines rather than being the work of a single person. Acceptable processes could include combinations of the following:

- Review of specific plant history and information from previous inspections
- Review of experience across similar industries or plants
- Expert elicitation of knowledge of structural integrity and materials

- Use of check-lists and mechanism descriptions
- Computer based expert systems

A review of specific plant history and information from previous inspections requires sufficiently detailed and reliable records. Deterioration mechanisms that have an incubation period or are time dependent, such as fatigue or stress corrosion cracking, may still be anticipated even if they have not yet been observed. Whilst experience of other similar plants can be helpful in identifying potential problem areas, caution is necessary. No two plants are ever exactly the same.

Expert elicitations are a good way of identifying potential deterioration mechanisms. Here a group of experts from different disciplines pool their knowledge and experience (6.2). The relevant disciplines might include design and stress engineers, welding metallurgists, corrosion chemists, as well as plant operators and inspectors. Competent Persons and independent experts can also bring cross-industry experience and knowledge of latest research.

Duty Holders and Competent Persons should be aware that it is not uncommon for two or more deterioration mechanisms to exist at the same time and to interact. Often detailed information about plant conditions will be required in order to exclude certain mechanisms. If this is not available, or not known with sufficient confidence, it is best to make conservative assumptions.

Care is required when applying computer based expert systems or check-lists. Commercial systems are valuable, but are not always comprehensive, and may restrict the independent evaluation of deterioration by the Duty Holder and the Competent Person. The key is to have good knowledge of deterioration mechanisms and the conditions for their occurrence, a good knowledge of the plant, and the ability to draw a link between them.

Whilst there are many mechanisms of deterioration and modes of failure associated with pressure systems and other containment structures, they can be roughly broken down into the following classes:

- Failure of protective devices
- Corrosion/erosion (general, local, pitting)
- Creep and high temperature damage
- Fatigue cracking
- Stress corrosion cracking
- Embrittlement
- Hydrogen blistering/stepwise cracking
- Brittle fracture
- Buckling

Appendix D describes of each of these deterioration mechanisms and modes of failure. Examples are given of equipment where these mechanisms can occur.

6.4. PROBABILITY OF FAILURE ASSESSMENT

6.4.1. Range of Methods

Risk analysis requires an assessment of the probability of failure. This is defined as the mean frequency with which the specified failure event would be expected to occur in a given period of operation, normally one year. If several years of operation are envisaged, for example the period between planned inspections, then the cumulative probability during the period should be determined. Ideally, this should be related to the future operation (e.g. number of start-ups, running or shutdown periods, or whatever is appropriate). In practice, however, it is normal to assume a constant rate of failure per year of operation unless failure rate data (e.g. bath tub curve) indicates otherwise.

When assessing the probability of failure, it is important to consider the future deterioration rate from all potential mechanisms. The rate of degradation may increase with time as a result of interaction between mechanisms (e.g. corrosion and fatigue). Factors such as overload, misuse, or accidental damage that cannot be easily predicted, should be assumed to occur at a constant average rate.

There are various methods that Duty Holders may apply for determining the probability of failure. These include qualitative, semi-quantitative and fully quantitative methods such as:

- Using judgement and experience from expert elicitation
- Failure rates for generic classes of equipment based on historical data
- Failure rates for generic equipment classes modified by equipment specific factors
- Check sheets with weighted answers
- Fault tree and/or probabilistic risk analysis
- Full structural reliability analysis - (e.g. probabilistic fatigue and fracture)

6.4.2. Qualitative Schemes

Qualitative schemes assess the likelihood of failure descriptively, using terms such as very unlikely, unlikely, possible, probable, or highly probable. Such terms are of little use unless criteria for the descriptive categories are defined. Ideally these criteria should be linked to a value of maximum failure probability.

Qualitative assessments should first establish the amount and quality of information that is known about the equipment. The likelihood of failure increases without adequate information and where there is uncertainty. Providing sufficient information exists, an assessment is then made of the level of threat to fitness-for-service in the future. Among the key factors to consider are the uncertainties in the current knowledge, the variability of deterioration rate, and the possibility of secondary failures and other credible events that could affect the equipment's integrity.

If Duty Holders do not have their own scheme, a suggested five point scale scheme in three steps is given below.

Step 1. Determine and score (on a scale of 1 to 5) the state of knowledge about the equipment considering:

- Design, material and fabrication
- Loading and operating history
- Inspection history, effectiveness and time since last inspection
- Operating environment
- Deterioration mechanisms and rate

The following table gives **example** scorings for different states of knowledge

State of knowledge about design, operation, condition and deterioration	Score
Full operating history and records of effective previous inspections available. Loading and operating conditions known, monitored and controlled. Deterioration rate known and monitored. Design etc. known.	1
Operating history or inspection records not fully complete. Loading and operating conditions known. Deterioration rate estimated within narrow limits. Design etc. known	2
Operating history or inspection records reasonably complete, Loading and operating conditions known. Deterioration rate estimated within broad limits. Design etc. known	3
Operating history incomplete. Previous inspection limited in coverage effectiveness. Degradation rate uncertain. Design etc. known.	4
Operating history unknown. Records of previous inspections unavailable. Loading and operating conditions unknown. Deterioration rate unknown. Design, material or fabrication unknown.	5

Step 2. Assess and score (on a scale of 1 to 5) the deterioration and threat to design or fitness-for-service margins of the equipment within the proposed inspection interval.

The following table gives **example** scorings for different assessments

Assessment of deterioration and fitness-for-service	Score
No potential for deterioration, damage, defects or degradation, identified by assessment and none detected in previous inspection. No threat to design/FFS margins.	1
Potential for deterioration, damage, defects or degradation identified by assessment but none detected by previous inspection. No threat to design/FFS margins predicted.	2
Deterioration, damage, defects or degradation, identified by assessment and/or detected by previous inspection. Assessment of deterioration indicates comfortable design/FFS margins in hand.	3
Deterioration, damage, defects or degradation, identified by assessment and detected by previous inspection. Assessment of deterioration indicates that design/FFS margins could be close to acceptable limits.	4
Deterioration, damage, defects or degradation identified by assessment and detected by previous inspection. Assessment of deterioration predicts design/FFS limits to have been exceeded.	5

Step 3. Choose the maximum score from steps 1 or 2 and assess likelihood of failure from table below

Maximum score	1	2	3	4	5
Likelihood of failure	Very Unlikely	Unlikely	Possible	Probable	Highly probable

6.4.3. Published Generic Failure Data

A number of surveys have been conducted to determine the root causes of failure and failure rates for generic classes of equipment (e.g. Class I pressure vessels, pipework, valves etc) based on historic synthesised data. In the UK, the survey of defects and potential and catastrophic failures conducted by Smith and Warwick (1983) (6.4) is the most comprehensive. HSE has more recently published information on the causes and numbers of failures in boilers and heat exchangers (Hawkins 1993) (6.5).

In the absence of other information, these statistics can provide an initial estimate of the failure frequency. However, care must be taken to ensure that the equipment being considered falls within the definition of the population in the survey. Cross-industry averages may not be the best measure if other information is available.

6.4.4. Semi-quantitative Schemes

Semi-quantitative schemes are based on modifying the failure frequency for the generic class of equipment by factors specific to the particular equipment. An example of this approach is contained in the API base resource document on RBI, API 581 (6.6). Factors are applied depending on the degree to which the particular equipment, its management and environment, may be better or worse than the industry average.

The main problem with this approach is that there are at present no clear industry standards against which to make comparisons. Semi-quantitative schemes are best suited to ranking equipment within a single facility where a consistent approach is possible. Their value in quantitative terms depends on the wider industrial experience of the RBI assessment team and the relevance of the generic failure data.

Fault tree analysis is a method for determining the probability of an event from the probabilities of pre-requisite preceding events or conditions (6.7). Whilst it is often used to analyse fault sequences, particularly in electrical or mechanical systems, there is relatively little experience of its application as a means to determine the probability of structural failures. Further applications of this method would be worthwhile.

6.4.5. Fully Quantitative Assessments

Fully quantitative assessments of the probability of failure on the basis of structural reliability analysis are rare. The main difficulty is in obtaining the appropriate statistical distributions of the loading and resistance variables and the computational time.

When such assessments are undertaken, justification of the relevance of the underlying data and mechanistic model is usually necessary. For example, probabilistic fatigue and fracture analyses depend critically on the assumptions made about the initial distribution of defects, the scatter in fatigue crack growth data, the spectrum of stress cycles, and the spread of fracture toughness data.

6.5. FAILURE CONSEQUENCES ASSESSMENT

For the purposes of meeting the requirements of Health and Safety legislation, the analysis of the consequences of failure of equipment should focus on the capacity of the failure and subsequent events to cause death, injury, or damage to the health of employees and the general population. Duty Holders will also legitimately consider the consequences of equipment failure to cause harm to the environment and the business and to incorporate measures to include these risks into the integrity management strategy.

In assessing the effects of the release of fluid resulting from failure of pressure systems and systems containing hazardous materials, Duty Holders should have knowledge of all the relevant factors including the following:

- The composition of the contained fluid and its physical/chemical properties
- The potential leak/break area considering the mode of failure and pipe/vessel size
- The pressure, temperature and rate of mass/energy release
- The total amount of fluid available for release
- Measures for detection of the leak/break and the means for its isolation
- The final phase of the fluid on release into the atmosphere
- The dispersal characteristics of the fluid at the site
- Mitigation systems such as water curtains and secondary containments

The subsequent consequences resulting from the release depend on the type of fluid and the energy contained in the system. Duty Holders should determine the potential for one or a combination of the following events that could endanger Health and Safety.

- **Flammable releases** – require a source of ignition, thermal effects tend to occur at close range, but explosion and blasts can reach over large distances from the centre, and can cause damage to surrounding equipment

Six possible outcomes can result from the release of a flammable fluid.

- i) Safe dispersal – Fluid disperses to a concentration below the flammable limit
 - ii) Jet flames – A high momentum release of a two phase fluid under pressure
 - iii) Vapour cloud explosion (VCE) – Rapid propagation of the flame front creating over-pressure damage
 - iv) Flash fires – A cloud of material burning without generating overpressure
 - v) Liquid pool fires – When a pool of flammable liquid ignites
 - vi) Fireball – When a large quantity fluid ignites after limited mixing with air, the most common scenario being a boiling liquid expanding vapour explosion (BLEVE)
- **Steam and hot gas releases** – steam causes scolding of personnel in the vicinity and can result in very severe injury. Hot gas can cause burns to people within range.
 - **Toxic releases** – both acute (short term) and chronic (long term) effects of chemical releases need to be considered in relation to the degree of exposure; gas clouds can extend large distances from the site of release. Liquids on the ground may enter water courses. Both employees and the general public may be affected.
 - **High pressure gas release** – compressed air and other gas blasts have the potential to cause physical injury to personnel in the vicinity and cause structural damage to surrounding equipment
 - **Missiles, pipe whip and equipment displacement** – have the capacity to cause physical injury to personnel in the vicinity and damage surrounding equipment

The number of employees and other persons on site and in the vicinity of hazardous systems are important considerations. Duty Holders should bear in mind variations between day and night-time working and between normal operation and outages. The number and density of the surrounding general population are also factors to be considered if the effects of releases could extend beyond the site boundary.

In some cases, such as the possible explosion of an isolated steam boiler, the assessment of consequences may be made by qualitative engineering judgements. In the case of the large chemical installation or storage facility, where there is potential for large flammable or toxic releases, the assessment of consequences may require detailed technical analyses considering the interaction with other systems.

Methods used to assess the release and the subsequent consequences should be appropriate, systematic and based on reliable data. Both qualitative judgements and quantitative analyses can be used. In some cases, it will be useful to consider cases of worst, typical and more favourable scenarios.

In the assessment of consequences to Health and Safety, two distinctions need to be drawn. Firstly there is the distinction between the risks to employees and those to the general public; secondly, the distinction between the capacity for single and multiple injuries/fatalities.

Duty Holders making qualitative assessments will often assess the consequences of failure in descriptive terms ranging from very high to very low. A common understanding of the meaning of these terms for Health and Safety is needed. The following table of definitions is suggested as a five point scale.

Category	Safety consequence	Health consequence
Very high	Multiple fatalities or serious injuries to employees and/or general public.	Long term health effects or acute short term effects to employees or general public.
High	Fatality or serious injury to a single employee. Off-site injuries needing treatment.	Long term health effects or acute short term effects to a single employee. Off-site health effects needing treatment.
Moderate	More serious injury to an employee needing hospital treatment.	Medium term health effects to an employee and lost time.
Low	Minor injury to an employee with full recovery.	Short term health effects with full recovery and lost time.
Very low	Injury to employee requiring only minor first aid at most.	Minimal health impact. No lost time.

6.6. DETERMINATION OF THE RISKS FROM EQUIPMENT FAILURE

The risk from equipment failure is the combination of the assessed likelihood and the consequence. Both the likelihood and the consequence (for Health and Safety etc.) should therefore be clearly identified and associated for each item of equipment under consideration. Qualitative expressions of risk such as moderate likelihood with high consequence are acceptable providing these terms are defined.

In quantitative terms, risk is the product of the probability of failure and the measure of the consequence. There may be different risks for different measures of consequence (e.g. deaths/year, £ loss/year). Various measures are available for quantifying risks to Health and Safety both to the individual employee and to society (local population). These include the fatal accident rate, and average and individual risk indices.

6.7. RISK RANKING AND CATEGORISATION

Risk matrices are a useful means of graphically presenting the results from qualitative risk analyses of many items of equipment. Risk matrices should, however, not be taken too literally since the scale of the axes is only indicative. The

simple matrix below is based on a linear scale of probability and consequence ranging from 1 to 5. The numbers in the cells are the product of the probability and consequence values.

5	5	10	15	20	25
4	4	8	12	16	20
3	3	6	9	12	15
2	2	4	6	8	10
1	1	2	3	4	5
Probability/ Consequence	1	2	3	4	5

This matrix draws attention to risks where the probability and consequence are balanced and to risks where either the probability or the consequence is high. Often matrices will be sectorised into regions covering different ranges of risk. As this example shows, the boundaries between regions depend on how the ranges are defined: changing the range of the red region from 21 to 25 to 20 to 25 could have a significant effect.

For quantitative analyses risk may be presented as a point a probability/consequence plot. When the plot has logarithmic axes, straight lines represent lines of constant risk. If risk is evaluated numerically, then equipment may be ranked in order of risk.

From these processes of ranking, Duty Holders should be able to identify the items of equipment presenting the greatest risks of failure. For the purposes of inspection planning, equipment may be categorised according to the type of risk. For example:

- Equipment where there is a known active deterioration mechanism
- Equipment where there is a high frequency of failure but consequences are low
- Equipment where the consequences of failure are high but the frequency is low
- Equipment where there is lack of data that could affect the risk

Known deterioration may be managed by programmed inspections and monitoring. High frequency/low consequence failures may be more of an operational nuisance than a risk to Health and Safety. However, frequent failures could also be an indicator of more fundamental weaknesses in design or management.

High consequence/low frequency failures are difficult to quantify since the events may never have occurred and are by their nature extremely rare. Often a cut-off is imposed at a level of consequence above which all levels of risks are considered significant. In these cases, an appropriate level of inspection during service is prudent to provide continuing assurance that the assumptions of the analysis remain valid.

Particular difficulties arise for new equipment or processes where there is a lack of the data needed to assess the risk (e.g. lack of design or materials data, operational or inspection history, or limited analysis of consequences). More frequent inspections may be necessary at the start-of-life to demonstrate integrity under operating conditions.

6.8. SUMMARY OF MAIN POINTS

- a) Risk analysis requires all stages in the process to be completed.
- b) Duty Holders may use different approaches to undertake a risk analysis.
- c) It is necessary to identify accident scenarios involving equipment failure.
- d) Duty Holders should identify deterioration mechanisms and failure modes.
- e) The likelihood/probability of failure may be assessed using qualitative, semi-quantitative or quantitative methods. The likelihood of failure is increased when there is lack of knowledge about the equipment, its operation or condition.
- f) It is necessary to evaluate the amount and rate of energy/product released in order to determine the consequences of failure. Duty Holders must assess the consequences of failure for the Health and Safety of employees and the public.
- g) The risk of failure is the combination or product of the probability and the consequence and may be expressed in qualitative or quantitative terms.
- h) Risk ranking can identify the highest risk equipment and different categories of risk.

6.9. REFERENCES FROM CHAPTER 6

- 6.1 Management of Health and Safety at work regulations 1999 (SI – 1999 – 3242), The Stationary Office.
- 6.2 Sundararajan C. (Raj), Probabilistic structural reliability handbook. Theory and industrial applications, ISBN 0 412 05481 7, published by Chapman and Hall 1995.
- 6.3 AIChE/CCPS, Guidelines for hazard evaluation procedures, Center for Chemical Process Safety, American Institute of Chemical Engineers, New York 1985.
- 6.4 Smith TA and Warwick RG, A survey of defects in pressure vessels in the UK for the period 1962 to 1978 and its relevance to nuclear primary circuits, International Journal of Pressure Vessels and Piping, 11, 127-166, 1983.
- 6.5 Hawkins G, Accidents on steam plant and hot water systems 1988 to 1992. HSE Specialist Inspector Reports No. 47, available from HSE.
- 6.6 API, Base resource document on risk based inspection – preliminary draft. API publication 581, Published by American Petroleum Institute 1996.
- 6.7 Green AE and Bourne AJ, Reliability technology, ISBN 0 471 32480 9, published by John Wiley 1984.

7. DEVELOPMENT OF THE INSPECTION PLAN

7.1. INSPECTION WITHIN AN INTEGRATED RISK MANAGEMENT STRATEGY

In managing the risk of failure and assuring continuing integrity, Duty Holders should remember that inspection is only one of a range of measures that are available to them. Depending on circumstances, other measures might include preventative maintenance, material sampling, pressure testing, continuous monitoring of the operating conditions, and improved operator training etc. In-service inspection should form part of an integrated risk management strategy containing a combination of appropriate measures.

Under the Pressure Systems Safety Regulations 2000 (PSSR) (7.1), users and owners of pressure systems must not allow the system to be operated unless there is a written scheme of examination drawn up and certified by a Competent Person. The scheme must identify the parts to be examined within the scope of the regulations, and the frequency and nature of the examination. These aspects of the written scheme should be determined on the basis of the information generated by the risk analysis.

7.2. SELECTION OF EQUIPMENT FOR EXAMINATION

In order to meet the statutory responsibilities for the safety of pressure systems, the PSSR require Duty Holders to have a written scheme for the periodic examination of the following parts of the pressure system:

- a) All protective devices
- b) Every pressure vessel and every pipeline in which a defect may give rise to danger
- c) Those parts of pipework in which a defect may give rise to danger

In the PSSR, ‘defects’ are not specifically defined, but should be interpreted broadly to mean any type of deterioration, damage, imperfection, or deviation from the design. ‘Danger’ is defined in relation to a pressure system as ‘reasonably foreseeable danger to persons from system failure, but (except in the case of steam). It does not mean danger from the hazardous characteristics of the relevant fluid other than from its pressure’.

The PSSR are concerned with risks arising from unintentional releases of stored energy. Risks of injury to persons resulting from escape of toxic, flammable or other hazardous materials are covered under other statutory provisions (e.g. Control of Major Accident Hazard Regulations - COMAH).

In terms of risk, this definition of ‘danger’ may be interpreted as a threat of system failure if a defect is present with reasonably foreseeable consequential injury to persons from the release of stored energy. The likelihood that a defect or other deficiency will be present is not a factor for excluding an item from consideration

within a written scheme. It may be taken into account later in the decision about whether examination is required and the periodicity of examination.

The responsibility for drawing up the scope of the examination within the written scheme lies with the Duty Holder, assisted if necessary by the Competent Person. The parts of the system included for examination will be specified together with those parts that can be justifiably excluded from examination. A Competent Person must certify the suitability of written schemes.

Generally, all protective devices and parts of pressure systems where the release of stored energy would give rise to danger should be included within the scope of periodic examination. Even if the release of stored energy is small, the consequences of the release of the product contained should also be taken into account, particularly if the materials are toxic or flammable. In these circumstances, periodic examination may be necessary in order to comply with the COMAH regulations.

The Approved Code of Practice (ACoP) in support of the PSSR (7.2) acknowledges that there may be parts of a pressure system that can be excluded from the scope of examination within the written scheme. These parts should be specified within the written scheme and the decision to exclude them from periodic examination justified on grounds that a defect would not give rise to danger. In order to arrive at a properly informed decision, Duty Holders are advised to seek advice from a person with relevant technical expertise and experience, who need not be the Competent Person, but must have experience of particular the type of system.

The ACoP to the PSSR gives guidance on equipment that might be excluded from periodic examination as follows:

- Small vessels with little stored energy which form part of a larger system.
- Pipework and associated components (including pipes, valves, pumps, compressors, hoses, bellows) except where:
 - i) Mechanical integrity is liable to be significantly reduced by deterioration, or
 - ii) There would be danger from the release of stored energy (e.g. high pressure jets, pipe whip).

Grounds for excluding parts from periodic examination depend on the advice provided by the person with the relevant technical expertise and experience. For example, it may not be necessary to examine, on a regularly defined basis, parts where it is not anticipated that deterioration will develop and propagate, or parts of a size or nature, or installed in a location, as to not constitute a danger in the event of failure. This does not, of course, exclude these parts from being specified within the written scheme, and the Duty Holder has the responsibility to inform the Competent Person of any defects or failures that may occur, or become apparent, or be suspected.

The current regulations and approved practice therefore enable a risk based approach to be used for the selection of equipment for examination. The difficulty arises in obtaining a consistent judgmental basis.

Duty Holders will specify the parts to be examined within the scope of the written scheme. The completeness of the written scheme should be carefully examined and reviewed and the reasons for the parts to be included and excluded from regular examination justified. In order for risk based principles to be applied to determine the frequency, extent and nature of examinations, the following information should be available for each part.

- Potential mechanisms and rates of deterioration in relation to the length of service
- Sites that may be particularly susceptible to deterioration or failure
- Potential types of damage, flaws, defects or degradation
- Tolerance of the part to damage, flaws, defects or degradation
- The probability or likelihood of failure arising from future operation
- The likely mode (e.g. leak or break, ductile or brittle fracture)
- The consequences of failure
- The risk category, or risk ranking, of the part

7.3. INITIAL EXAMINATION PRIOR TO ENTERING SERVICE

An initial examination should normally be carried out following installation of new equipment before it is put into service for the first time. Duty Holders and Competent Persons should decide on the form of the initial examination. Consideration should be given to the results of the conformity assessment of design and fabrication, and the effectiveness and results of fabrication inspections.

Suitable documentation should be available to confirm that the equipment is in a satisfactory condition after fabrication. In this case, the initial examination of the equipment need not be so thorough and a visual examination may suffice. The initial examination can concentrate on verifying the correctness of the installation, the integrity of connections, and look for signs of damage resulting from transit, installation, or other external conditions.

Sometimes there may doubt about the quality of manufacture, fabrication inspection, or the level of conformity assessment in relation to the proposed duty. At other times, suitable documentation is not available even though the equipment is believed to be satisfactory. Both these circumstances give rise to increased uncertainty and hence increase the risk, and a thorough initial examination of the equipment as well as the installation should be included in the written scheme.

New equipment conforming to the Pressure Equipment Directive (PED) will be supplied with a CE marking and an EC declaration of conformity. The PED categorises equipment based on the amount of stored energy and the consequences of failure, and sets different modules of conformity assessment depending on the category of duty. The intent is that new pressure equipment will be of a standard consistent with the risk of its intended application, but until the PED is in fully in force and manufacturers have gained experience of assigning equipment to the correct category, Duty Holders are advised to be cautious.

For equipment purchased second hand, or being re-used from another application, lack of service and inspection history increases the uncertainty and hence the risk. An appropriate re-examination to provide a benchmark is essential if the previous service history is incomplete, or if previous inspection results are not available, or are judged ineffective, or when modifications or repairs have been made.

7.4. FIRST EXAMINATION AFTER ENTERING SERVICE

The PSSR recognise that the first examination after equipment enters service is extremely important to establish a benchmark of its condition under the operating conditions. An early examination can detect deterioration resulting from inadequate design, manufacture, or knowledge of the actual operating environment. Without favourable operating experience, the equipment must be judged to have a higher risk of failure, and some authorities, including the Institute of Petroleum, do not accept risk assessments until after the first examination.

Current industrial practice is to carry out the first thorough examination within the period given by the written scheme, and in any case, not greater than 24 months after the initial examination. For this period to be extended, favourable operational experience of the manufactured equipment under the operating environment would need to be demonstrated by means other than by examination, for example, by on-line monitoring. This should be supported by relevant industrial experience elsewhere.

The timing of the first examination should take account of aspects such as:

- The level of conformity assessment of the design and manufacture
- The extent of knowledge or uncertainty about the actual operating environment
- The tolerance of the equipment in the event of inadequate design or manufacture.

When a risk analysis has been made of several items of new equipment, the risk category or risk ranking of each item can be used to prioritise the timing of the first examination. This might allow the first examinations to be staggered. Even if they are several nominally identical items, all items must be examined within the first examination period set for each item.

7.5. INTERVALS BETWEEN EXAMINATIONS

7.5.1. Relevant Factors

The PSSR do not prescribe specific intervals between examinations. It requires the Competent Person to use judgement and experience to set an appropriate inspection interval for each part based on the relevant information. Different parts of a pressure system may be examined at different intervals depending on the degree of risk associated with each part.

The general aim should be to ensure that examinations are carried out sufficiently frequently to identify, at an early stage, any deterioration or malfunction which is likely to affect the safe operation of the system. The consequences of failure giving

rise to danger are not a primary consideration because these have already been taken into account when selecting parts for examination. The ACoP (7.2) draws attention to a number of factors affecting the likelihood of failure that should be taken into account when deciding on the appropriate interval between inspections:

- The safety record, age and previous history of the system
- Any generic information available about the particular type of system
- Its current condition
- The expected future operating/loading conditions (especially arduous)
- The quality of fluids used in the system
- The user's standard of supervision, operation, maintenance, and inspection
- The applicability of any on-line monitoring
- Earlier legislation fixing maximum intervals for some types of equipment

When determining appropriate intervals within a risk based framework, it is appropriate to take the following additional factors into account.

- Postulated degradation mechanisms (as far as these are known)
- The rate of deterioration
- Tolerance to defects
- The likelihood of failure during the proposed interval
- Uncertainties in the above (particularly the current condition and degradation rate)

7.5.2. Approaches for Setting Maximum Inspection Intervals

Established practice is to use one or more of the following approaches as a basis to set the maximum intervals between inspections.

- Historical experience of the type of equipment (e.g. boilers, air receivers)
- Industry guidelines for classes of equipment based on in-service experience
- As a prescribed percentage of the estimated residual life or the design life

(a) Historical experience

The approach of the Factory Acts was to specify fixed intervals between inspections for steam and air equipment based on historical operating experience and failure data. For steam plant the period was 14 months, unless conditions were arduous, and for steam receivers, it was in the range of 26 to 38 months. For air receivers it varied from 24 to 48 months, although it could be as long as 72 months when conditions were favourable.

In many cases, however, this approach was considered to be too conservative. Certificates of Exemption were granted under the Acts for particular types of equipment such as boilers at large electricity generating plants.

(b) Industry guidelines

The Institute of Petroleum (Model Codes of Safe Practice Parts 12 and 13) (7.3) and SAFed (Guidelines on Periodicity of Examinations) (7.4) have issued guidelines recommending maximum service intervals between inspections.

The Institute of Petroleum's Codes grade equipment based on a qualitative assessment of the rate of deterioration from the first and subsequent examinations. Maximum examination intervals between 2 and 12 years are recommended depending on the type of equipment (e.g. process pressure vessels) and the assessed grade. Successive examination intervals can be extended (or reduced) if the grade of the equipment is changed. This may happen following examinations where favourable (or unfavourable) operating experience of the equipment, or identical plant on similar duty, is observed.

When applying industry guidelines, the extent of operating experience is a key factor to be considered. Appropriate margins are necessary to allow for uncertainties and the reliability and relevance of the supporting data for the existence and rate of deterioration. For example:

- The use of published generic design data, code default values, and corrosion rate tables without any field data must be viewed with scepticism: corrosion rates can be very sensitive to the specific material and process conditions.
- Data or measurements from inspections with limited or unproven effectiveness, or laboratory testing with simulated process conditions, can be considered to have only moderate reliability.
- Field measurements from proven effective inspections of similarly aged equipment can provide data with high reliability.

(c) Remnant life

The remnant life approach to determining inspection intervals is based on calculating the remaining life of the equipment based on its tolerance to deterioration, defects or damage and the rate of deterioration. The tolerance to deterioration is determined by assessing fitness-for-service at future times according to the deterioration predicted. Methods such as those given in API 579 and BS 7190 may be used (7.5, 7.6).

An inspection interval can then be prescribed as a percentage of the remaining life. The percentage selected needs to take uncertainties and reliability of the data into account. As a guide, API 510 and 570 (7.7, 7.8) states that the maximum interval between inspections should not exceed 50% of the estimated remaining life based on the measured corrosion rate.

The SAFed Guidelines (7.4) recommend inspection intervals for pressure vessels subject to creep, fatigue and other remnant life conditions. These are based on the length of prior service as a proportion of the predicted total life calculated at design

or re-evaluated during service (i.e. the percentage of the calculated life used). During service up to 80% of the calculated life, examination intervals should be based on 20% of the calculated life, but when prior service exceeds 80% of calculated life, examination intervals should be based on 10% of the calculated life. These criteria are limited by maximum intervals specified for different classes of vessel.

The assessment of residual life needs to take all known and potential deterioration mechanisms into account. Calculations should be based on conservative assumptions, and contain adequate margins to allow for uncertainties. The reliability of the available inspection and materials data is a key consideration in assessing the current condition of the equipment, the rate of deterioration, and the continued fitness-for-service.

Some deterioration mechanisms (e.g. fatigue crack growth, stress corrosion cracking) do not proceed at a constant rate but progressively increase with time or initiate late in life. The residual life calculation is then no longer a simple ratio of deterioration tolerance to deterioration rate. In these cases, a fixed interval based on a fraction of the remnant life may not be appropriate and there may be a need for more frequent inspection towards the end of life.

7.5.3. Risk Considerations

When having taken account of the relevant factors and established approaches for determining maximum examination intervals, a decision on the appropriate frequency of examination is needed for each item of equipment. The PSSR allow a judgement to be made on a suitable interval. Consideration of risk is able to influence that judgement.

Approaches to setting examination intervals based on a quantitative risk analysis would assess the accumulated risk of failure during the proposed interval between inspections. Ideally, the examination interval would be set so that the accumulated risk never rises above an appropriately low level within a tolerable risk framework. However, this is currently difficult to justify because methodology and data are not sufficiently substantiated together with the difficulty of defining an acceptable risk target.

It is therefore suggested that maximum examination intervals are determined using one of the established approaches. This interval could then be modified based on the relevant factors and results of the risk analysis. Some latitude to extend intervals might be acceptable when, in the opinion of the Competent Person, the risks were evidently low, but there would be grounds to reduce intervals when higher risks were identified.

For example, based on the descriptive categories of likelihood and consequence of failure in Section 6, consideration could be given to extend intervals when either:

- Likelihood or consequence of failure is very low and the other is moderate or lower,
- Low likelihood is combined with low consequence.

Conversely, it would be prudent to impose a shorter examination interval when either:

- Likelihood or consequence of failure is very high and the other is moderate or higher
- High likelihood is combined with high consequence.

Examination intervals should have a degree of conservatism that reflects the amount of uncertainty in the estimated future risk. Equipment should not be allowed to deteriorate to a point where the minimum design basis, or fitness-for-service, could be threatened.

After equipment is examined, the Competent Person will give an opinion in the report about the suitability, or otherwise, of the written scheme of examination. The report will specify the date after which the equipment may not be operated without further examination. There is therefore opportunity to modify both the written scheme and the examination date to take account of events, or circumstances, or observations, that could alter the original basis for setting the examination interval.

7.6. DEALING WITH SAMPLE INSPECTIONS OF NOMINALLY IDENTICAL ITEMS

Under some circumstances, Duty Holders may choose to group items of equipment of the same type, material, construction, and experiencing the same process conditions. Proposals may then be considered for examining a sample of the items at each outage. In dealing with sample inspection, the following principles should apply.

In practice, no two items of nominally identical equipment are ever the same. There can be differences for all kinds of reasons: design, material, construction, welding, fabrication defects, service history, siting, connections to other equipment, system loadings, external hazards, degradation rate etc. The effect of such differences on deterioration and the risk of failure is usually hard to assess.

With this in mind, the ACoP to the PSSR (7.2) states that all parts of the system must be examined within the period specified for each part in the written scheme of examination. Each part should therefore be considered as an individual item within the written scheme. Whilst the examination period applies to the part and not to the group, it is likely that a group of similar parts will have the same period.

Where there are several nominally identical items of equipment on a site, operated by the same Duty Holder, that have been individually assessed to have the same period of examination, it is permissible to use a form of staged examination. The ACoP gives the hypothetical example of a written scheme for four identical vessels and specifies a frequency of examination of five years. It is acceptable to examine a different vessel each year within the group of four so that all four vessels have each been examined once within the five year period.

The sequencing of examinations of a group of equipment within the maximum period may depend on the relative risk and any differences in the information available. For example, vessels sited nearer to people should be examined preferentially to those further away. Equipment where information is not available should be examined first.

After the examination of each item of equipment, the Competent Person must state in the report whether the current scheme of examination is still suitable and specify the date after which the equipment may not be operated without further examination. This allows the Competent Person to modify the written scheme and to have flexibility in setting the next examination date. Where the item of equipment is part of a group, the Competent Person may want to consider the examination results and intervals of the other items in the group.

7.7. EXTENT OF EXAMINATION

Inspection is expensive and the extent of coverage becomes crucial. Duty Holders should determine whether the threats to integrity of each item of equipment are likely to be general (such as general corrosion) or localised to specific sites. There may be a decreasing return on inspection in terms of risk reduction if a particular mechanism is shown to be absent, or conversely, if there is widespread attack.

Sites that may be susceptible to deterioration or failure (such as welds, high stress regions, penetrations, saddle points, exposed or fired surfaces, and liquid level interfaces) should be identified and examined within the written scheme. The selection of welds for examination is particularly pertinent in the case of large welded structures such as storage tanks and spheres. The Duty Holder should rank the welds within the structure according to their relative risks of failure considering aspects such as:

- Fabrication (shop/site, access etc)
- Stress
- Service conditions (fatigue and environment)
- Function within the structure and redundancy
- Consequences in the event of failure
- Degree of uncertainty in the above

One of the pre-requisites for excluding welds from examination is to demonstrate that the welds were fabricated without significant defects. Access to, and knowledge of, the original records of the fabrication inspections or the records of inspections in-service are key requirements. The Duty Holder will need to assess the effectiveness of the fabrication, or subsequent, inspections to ensure that they were capable of detecting potential defects that could be significant to the risk of failure in-service.

Weld repairs are often a source of problems because of the risk of creating further welding defects, high residual stresses and strain-aged heat affected zones in the as-welded condition. Duty Holders should be expected to know the location of weld repairs and any additional factors that might make these sites susceptible to failure. Periodic examination of weld repair regions is normally a priority.

HSE commissioned research (7.9) to investigate the proportion of welds that needs to be sampled and examined to obtain assurance about the density of defects. Statistical theory may be applied assuming that defects are randomly distributed. Usually, however, defects are not randomly distributed and many other factors will determine the extent of the examination.

7.8. NATURE OF EXAMINATION

A wide range of inspection techniques is available. It is the purpose of risk based inspection to select the techniques that are most effective for the type of in-service deterioration predicted. Inspection techniques may also need to detect fabrication defects if there is a chance of these remaining in equipment entering service.

The PSSR require written schemes of examination to specify the nature of the examination. This states the inspection techniques and procedures to be applied and is subject to approval by the Competent Person. Duty Holders and the Competent Person should be able to demonstrate that the inspection is fit for its purpose in terms of:

- Reporting level (the required minimum deterioration to be reported).
- Effectiveness (capability of the inspection to detect and size the minimum reportable deterioration).
- Reliability (the probability of detection and sizing accuracy).

Reporting levels should ideally relate to fitness-for-service criteria. These should be based on the tolerance of the component to deterioration, the possible deterioration rate, and the interval until the next examination. A comfortable margin should exist between the reporting level and any defects that are of concern in order to allow for uncertainties in the basic data.

The effectiveness of inspection techniques and procedures depend on the objectives of the inspection (e.g. detection or sizing) and the characteristics of potential defects. These characteristics include the defect type, size, position and orientation. It is good practice to review the likely effectiveness of the inspection proposed for each site, particularly where there is complex weld geometry, unfused land, poor surface finish, or restricted access.

Human factors can affect inspection reliability. Inspection procedures should therefore incorporate measures to maximise the chances of obtaining an effective examination. In addition, they should also take the risks faced by inspectors into account. Chapter 8 reviews ways that Duty Holders can select and qualify inspection techniques and procedures to achieve the required levels of effectiveness and reliability.

Advances in NDT techniques have now made it possible to determine material integrity remotely without direct access to the material under test. NDT can be carried out through paint, coatings or insulation and material can be tested that is at a

long range from the access point. These are known as remote screening techniques and their capability is reviewed in Section 8.2.

Advances have also made it possible to test material for corrosion or defects on the opposite surface to where there is access. The advantage of these techniques is that internal surface of pressure vessels and tanks can be examined from the outside surface. When this avoids the need to enter the equipment for internal examination, it is known as non-invasive inspection.

There are advantages for health and safety in non-invasive inspection when this can be carried out effectively and reliably. These include a reduction of risks to personnel entering confined spaces. Non-invasive inspection can also make invasive inspection more efficient and effective by targeting the most suspect areas in advance and thereby reducing the time inspecting internal surfaces

Other factors influencing the decision to inspect non-invasively include the susceptibility of the process materials to atmosphere, the availability of favourable invasive historical inspection data, and the relative costs associated with invasive and non-invasive inspection. Techniques for non-invasive inspection are relatively new, and so Duty Holders need to be able to demonstrate sufficient confidence in their capability and coverage for each application.

7.9. OTHER MEASURES FOR RISK MITIGATION

7.9.1. Examples

Under some circumstances, it is appropriate for Duty Holders to apply measures other than inspection for condition monitoring and managing the risk of failure from deteriorating equipment. Such measures are important when inspection by NDT is impossible or ineffective. The following gives some examples.

- Material sampling, replication or micro-structural examination may be appropriate if micro-structural degradation of the material properties is suspected by, for example, high temperature creep or hydrogen embrittlement.
- On-line load monitoring can be used to estimate fatigue damage.
- Materials for low temperature service should be selected when brittle fracture due to low temperature operation or cold climate is a threat.
- Engineering safeguards and/or operator training can prevent or reduce the severity of operating transients and excursions.
- Laboratory work to quantify the corrosion rate with high reliability can be a good alternative to plant inspection.

7.9.2. Pressure Testing

Design and construction codes require pressure tests before service ‘to demonstrate, as far as is possible with a test of this nature, the integrity of the finished product’.

They provide a basic proof of leak tightness and adequacy of design for pressure loading. Pressure testing can also be applied in-service to provide assurance of design and fabrication quality of repairs and/or modifications. Other benefits from carrying out a pressure test include:

- Redistribution of local stresses. The initial application of a pressure test will cause localised yielding at stress concentrations and a redistribution of the stress. This is quite acceptable and is beneficial in reducing stress concentrations during normal service.
- Blunting of cracks If there are cracks in a vessel, perhaps from welding during construction or repair, then those cracks will tend to become blunt ended and therefore less likely to propagate.
- As an addition to a visual inspection, particularly where there is a lack of access for inspection e.g. jacketed pan, platen.
- As a demonstration of adequacy of design of complex geometries by strain gauging.
- As a means for detecting gross loss of wall thickness.

Pressure testing can only provide assurance of design for pressure loading under self weight plus that of the test fluid. Limitations are that it cannot simulate other operational conditions such as:

- Thermal gradients.
- Temperature differentials between components (e.g. heat exchanger shell to tube plate).
- Applied loadings from pipe attached to nozzles or external attachments.
- Wind loadings.

Other limitations and disadvantages with pressure testing include:

- The risk of unnecessary brittle fracture if the toughness is reduced at the test temperature in vessels designed to operate at higher temperatures.
- Not revealing the susceptibility to brittle fracture during service of vessels designed to operate temperatures below the test temperature.
- The possibility of weakening the vessel by deformation or tearing of defects without detection by observable failure.
- Very high pressures would normally be required to detect all defects of concern and unnecessary damage to the equipment could result (7.11).

- They do not provide any assurance of future fitness-for-service against deterioration mechanisms where defects can initiate in-service, such as thermal fatigue, vibration or by environmental effects.
- Their value in providing assurance of integrity where there may be pre-existing defects depends on the rate of deterioration, if this is known, but it can be very limited if the deterioration rate is significant.

Pressure testing is not a substitute for inspection as a means for detecting defects and cannot be relied upon as the sole argument for future integrity. It should only form part of a risk based integrity management strategy where there are clear reasons and benefits to do so. There may, however, be practical difficulties in carrying out pressure tests to systems and equipment in-service, and in these cases, an alternative strategy to provide assurance is often preferable.

7.9.3. Leak-Before-Break

There is increasing interest in ‘leak-before-break’ as a safety argument. It has to be demonstrated that any credible defect would grow through the containment wall in a stable way and create a detectable leak. Methods to assess leak-before-break are given within the flaw assessment methodologies of R6 and BS 7910 (7.10 and 7.6)

Leakage of fluid through a penetrating defect will often not be tolerable, for instance, when the fluid is high pressure steam, toxic or flammable, or has environmental consequences. When leak-before-break does not ensure safety, prevention of leakage failure by inspection and/or other integrity management measures is necessary. In general, as any leakage is undesirable, leak-before-break should not be an argument for avoiding inspection where this is reasonably practicable.

The main use of leak-before-break is in providing an argument for the stability of penetrating defects and forewarning of catastrophic failure within a multi-legged safety case for equipment where it is not possible, or practicable, to inspect. For validity, the postulated leakage must be detectable and the consequences manageable within the context of the total safety case. Leak-before-break has relevance for tanks and vessels that are doubly contained providing that the outer shell is designed to withstand the fluid at its full pressure and the interspace is effectively monitored.

7.10. DEALING WITH THE UNKNOWN

Inspection is of most use when there is the possibility of active deterioration mechanisms, uncertainty about the actual condition of the equipment or the degradation rate. In-service inspection is best suited to detect deficiencies that evolve over a period of time. Accidental damage and other random events have a low but constant rate of occurrence and the probability builds up over a period of time.

There are situations where, after thorough risk analysis, no active degradation mechanisms are identified. However, even in the most well controlled plants, some

uncertainty will exist. For equipment whose failure would cause high consequences, there is benefit from periodic spot checks for the unanticipated mechanism.

7.11. SUMMARY OF MAIN POINTS

- a) In-service inspection is not the only means to manage the risk of failure and other measures may be appropriate in an integrated risk management strategy.
- b) The written scheme must cover all protective devices and parts of equipment where a defect may give rise to danger.
- c) The selection or exclusion of equipment from examination must be justified.
- d) Initial pre-service examination of new or second hand equipment should normally be carried out following installation, but the extent and form depends on the information available from previous examinations and its reliability.
- e) Without favourable operating experience of equipment in-service, demonstrated by the first in-service examination or other means, the equipment must be judged to be of a higher risk of failure.
- f) A wide range of factors relating to the risk should be considered when setting the examination interval for each item of equipment within the written scheme.
- g) The maximum interval between examinations should be determined using established approaches allowing for potential uncertainties in the information available and the assessed risk of failure.
- h) Items of similar equipment within a group must be considered for examination as individual items, but a form of staged examination is permissible and the written scheme and dates for examination may be modified as a result.
- i) The sites most susceptible to failure should be determined and examined preferentially, and risk principles can be used to justify schemes for sample weld examination.
- j) Duty Holders should select inspection methods whose effectiveness to detect potential deterioration has been demonstrated.
- k) The safety of high failure consequence equipment can benefit from periodic spot checks for unanticipated deterioration mechanisms.

7.12. REFERENCES FROM CHAPTER 7

7.1 'The Pressure Systems Safety Regulations 2000', SI-2000-128. The Stationary Office.

7.2 Health and Safety Commission: 'Safety of pressure systems – Approved code of practice', L1222, ISBN 0 7176 1767X, published by HSE Books 2000.

- 7.3 Institute of Petroleum, Model code of practice (Parts 1 and 2), available from the Institute of Petroleum.
- 7.4 Safety Assessment Federation: 'Pressure systems guidelines on the periodicity of examinations', PSG1, ISBN 1901212106, available from the Safety Assessment Federation.
- 7.5 American Petroleum Institute: 'Recommended practice for fitness for service', API 579, available from the American Petroleum Institute.
- 7.6 British Standards: 'Guide on methods for assessing the acceptability of flaws in metallic structures', BS 7910:2000, ISBN 0 580 33081 8, 2000.
- 7.7 American Petroleum Institute: 'Inspection code for pressure vessels', API 510, available from the American Petroleum Institute.
- 7.8 American Petroleum Institute: 'Inspection code for piping', API 570, available from the American Petroleum Institute.
- 7.9 Georgiou G A: 'Probabilistic models for optimising defect detection in LPG welds', Proc Annual Conf of BINDT 2000, available from British Institute of Non-Destructive Testing.
- 7.10 British Energy: 'R6: Assessment of the integrity of structures containing defects – Revision 3'. February 1997, available from British Energy, Barnwood, Gloucs.
- 7.11 Cowan A and Picker C: 'Some considerations of overpressure test/limiting defect size arguments for ferritic pressure vessels'. Int. J. Pressure Vessels and Piping, 15, 105-123, 1984.

8. ACHIEVEMENT OF RELIABLE INSPECTION

This chapter aims to highlight the main issues to be addressed in order to achieve reliable inspection. The application, capability, and limitations of available inspection techniques are reviewed. Methods used for assessing inspection performance and ensuring reliable inspection for different applications are described.

8.1. LOCAL INSPECTION METHODS/TECHNIQUES

8.1.1. Main Inspection and NDT Methods

This Section describes each of the main inspection and NDT methods. Tables 1 and 2 identify the method(s) most appropriate for the detection of surface and internal flaws in ferritic and austenitic steels. Table 2 is specific to the inspection of welds. Table 3 identifies the method(s) most appropriate for the detection of specific deterioration types and the sizing capability associated with each method. Table 4 expands on Table 3 for some of the specific deterioration types identified, i.e. cracking and corrosion/erosion.

a) Visual Inspection (VT):

Visual inspection, with or without the use of optical aids, is performed with the aim of detecting surface-breaking flaws. There are a variety of optical aids available to the visual inspector ranging from simple hand-held magnifiers to specialist devices such as fibre-optic endoscopes for the inspection of restricted access areas. The capability of visual inspection is heavily dependent on the surface condition of the component and the level of lighting available.

Limitations - Fairly limited capability unless special optical aids are used. Method usually requires supplementing with other methods/techniques to confirm the presence of flaws and for sizing.

Typical Equipment Used:

- Eyes
- Optical Aids (Magnifiers, Borescopes, Fibrescopes)
- Film and Video Cameras for Recording.

Relevant Personnel Certification. The following schemes are in compliance with EN 473/ISO 9712:

- ◆ PCN¹: Personnel Certification is available at Levels² 1, 2 and 3 (General Engineering category - covers Welds, Castings and Wrought Products) and at Level 2 and 3 (Welds, Castings and Wrought Products categories).

¹ PCN is the UK national certification scheme for NDT personnel; the scheme is managed and administered by the British Institute of NDT. The PCN scheme covers certification in accordance with EN 473 - General Principles for Qualification and Certification of NDT Personnel.

² Level 1 - At this level, personnel can carry out NDT operations according to written instructions under the supervision of Level 2 or Level 3 personnel. Level 2 - At this level, personnel can perform and supervise NDT according to established or recognised procedures. Level 3 - At this level, personnel can direct any NDT operation for which they are certificated.

- ◆ CSWIP³: Personnel Certification is available at Levels 1 and 2 (General Engineering or Welds categories) and at Level 3 (General category - Welds, Castings and Wrought products).

Relevant Standards:

- BS EN 970:1997 - Visual Examination of Fusion Welds (replaces BS 5289:1976).
- BS EN 12454:1998 - Visual Examination/Castings.
- BS ISO 3057:1998 - Metallographic Replica Techniques of Surface Examination (replaces BS 5166:1974).
- BS ISO 3058:1998 - Aids to Visual Inspection/Selection of Low-Power Magnifiers (replaces BS 5165:1974).

b) Penetrant Testing (PT):

In penetrant testing, liquid penetrant is drawn into surface-breaking flaws by capillary action; application of a developer draws-out the penetrant in the flaw producing an indication on the component surface. Penetrant testing is a low-cost method to apply and is very fast (large area coverage). It is usually a six stage process:

- (i) Surface cleaning.
- (ii) Application of penetrant to component surface.
- (iii) Removal of excess penetrant.
- (iv) Application of developer.
- (v) Inspection of component surface for flaws
- (vi) Post-cleaning.

Penetrant testing can be applied to any non-porous clean material, metals or non-metals, but is unsuitable for dirty or very rough component surfaces. Red-dye penetrant is the most commonly used; fluorescent penetrants are used when maximum flaw sensitivity is required. Penetrant testing can be fully automated, however, in the field, the method is manually applied.

Limitations - Can only detect flaws open to the surface (the component surface on which the penetrant is applied). In addition, the flaw must not be filled with foreign material as this prevents the penetrant from entering the flaw. Cannot determine flaw through-thickness dimension.

Typical Equipment Used:

- Solvent Cleaner
- Red-dye Penetrant
- Developer (+ UV Lamp for Fluorescent Penetrant)

³ CSWIP – Certification Scheme for Weldment Inspection Personnel, operated by The Welding Institute (TWI).

Relevant Personnel Certification:

- ◆ PCN: Personnel Certification is available at Levels 1, 2 and 3 (General Engineering category - covers Welds, Castings and Wrought Products) and at Level 2 and 3 (Welds, Castings and Wrought Products categories).
- ◆ CSWIP: Personnel Certification is available at Levels 1 and 2 (General Engineering or Welds categories) and at Level 3 (General category - Welds, Castings and Wrought products).

Relevant Standards:

- BS EN 571-1:1997 - General Principles (replaces BS 6443: 1984).
- BS EN 1371-1:1997 - Liquid Penetrant Inspection/Castings (replaces BS 4080: Part 2:1989).
- BS EN 10228-2:1998 - Penetrant Testing of Steel Forgings.
- BS EN 1289:1998 - Acceptance Levels/Welds.

c) Magnetic Particle Inspection (MT or MPI):

In MPI, the component is magnetised either locally or overall. If the component is sound the magnetic flux is predominantly inside the material, if, however, there is a surface-breaking flaw, the magnetic field is distorted, causing local flux leakage around the flaw. The flux leakage is displayed, by covering the surface with very fine iron particles, usually suspended in a liquid. The particles accumulate at the regions of flux leakage revealing the flaw as a line of iron particles on the component surface.

MPI is applicable to all metals that can be magnetised. With MPI, it is important to ensure that the direction of the magnetic flux is appropriate for the flaws expected. A variety of equipment is available, the most common method of magnetisation being the application of a permanent or electromagnet (AC yoke) to the component surface. The equipment is manually operated.

Limitations - Can only detect flaws in ferromagnetic materials. Can only detect surface flaws (some sub-surface capability exists with this method but detection can be unreliable). Cannot determine flaw through-thickness dimension.

Typical Equipment Used:

- AC Yoke
- Black Magnetic Ink
- White Background Paint (UV Lamp for Fluorescent Ink)
- Flux Indicators

Relevant Personnel Certification:

- ◆ PCN: Personnel Certification is available at Levels 1, 2 and 3 (General Engineering category - covers Welds, Castings and Wrought Products) and at Level 2 and 3 (Welds, Castings and Wrought Products categories).

- ◆ CSWIP: Personnel Certification is available at Levels 1 and 2 (General Engineering or Welds categories) and at Level 3 (General category - Welds, Castings and Wrought products).

Relevant Standards:

- BS EN 1290:1998 - Magnetic Particle Examination of Welds (replaces BS 6072:1981).
- BS EN 1369:1997 - Magnetic Particle Inspection/Castings (replaces BS 4080: Part 1: 1989).
- BS EN 1291:1998 - Acceptance Levels/Welds.
- BS 6072:1981 - Methods for Magnetic Particle Flaw Detection.
- BS PD6513:1985 - A Guide to the Principles and Practice of Applying Magnetic Particle Flaw Detection in Accordance with BS 6072.

d) Eddy Current (ET):

In eddy current testing, a coil carrying an AC current is placed close to the component surface. The current in the coil generates circulating eddy currents in the component close to the surface and these in turn affect the current in the coil by mutual induction. Surface-breaking flaws and material variations in the component affect the strength of the eddy currents. Therefore, by measuring the resultant electrical changes in the exiting coil, flaws etc. can be detected.

Eddy current testing is applicable to all electrically conducting materials. Prior to their use eddy current systems require calibration, usually on test pieces. With this method of testing, sensitivity to flaws can be very high. The equipment is manually operated.

Limitations - High level of operator skill required to interpret signals. Spurious indications can result from (i) local variations in material permeability (especially near welds), and (ii) probe lift-off (on rough surfaces). Can only really detect surface flaws (some sub-surface capability does exist but detection can be unreliable). Limited capability for determination of flaw through-thickness dimension.

Typical Equipment Used:

- Eddy Current Flaw Detector (meter/oscilloscope type)
- Probes
- Calibration Test Pieces

Relevant Personnel Certification:

- ◆ PCN: Personnel Certification is available at Levels 1, 2 and 3 (Welds and Wrought Products categories).
- ◆ CSWIP: Personnel Certification is available at Levels 1 and 2 (Welds).

Relevant Standards:

BS EN 1711: 2000 – Non-destructive examination of welds – Eddy current examination of welds by complex plane analysis.

e) Radiography (RT):

In radiographic testing, a source of X or gamma radiation is used to produce an image of the component on photographic film (by placing the radiation source on one side of the component and the film on the other). Following exposure to radiation, the film is then processed and then viewed on an illuminated screen for visual interpretation of the image. Radiography gives a permanent record (the exposed film), which is a major advantage of the method, and is widely used to detect volumetric flaws (surface and internal).

X-ray equipment ranges from about 20kV to 20MV (the higher the voltage the greater the penetrating power of the radiation and the greater the thickness of component that can be tested). Gamma radiography is carried out using radioactive isotope sources (e.g. Cobalt-60, Iridium-192) although its sensitivity is generally less than that achievable by X-ray radiography. It is widely used for fieldwork because of its greater portability.

Limitations - Limited capability for the detection of (planar) flaws that are not oriented parallel to the radiation beam, e.g. lack of side-wall fusion. Cannot determine flaw through-thickness dimension. For most applications internal access is required (as well as external). For on-site testing, radiation safety is a major issue.

Typical Equipment Used:

- X-ray Unit/Gamma Source
- Film
- Processing Unit
- Viewing Facility

Relevant Personnel Certification:

- ◆ PCN: Personnel Certification is available at Levels 1, 2 and 3 (Welds and Castings categories).
- ◆ CSWIP: Personnel Certification is available at Levels 1, 2 and 3 (Welds).

Relevant Standards:

- BS EN 444: 1994 - General Principles for Radiographic Examination of Metallic Materials by X and Gamma Rays.
- BS EN 1435: 1997 - Radiographic Examination of Welded Joints (replaces BS 2600:Part 1:1983, BS 2600:Part 2:1973, BS 2910: 1986 and BS 7257:1989).
- BS EN 462-3: 1997 - Image Quality Classes for Ferrous Metals.
- BS EN 12517: 1998 - Acceptance Levels/Welds.
- BS 2737: 1956 - Interpretation of Radiographs/Castings.

f) Conventional Ultrasonic Testing (UT):

i) Flaw detection

In ultrasonic flaw detection, a beam of high frequency sound (MHz range) from a small probe is used to scan the component material for flaws. This method of testing is used to detect both surface and internal flaws (planar and volumetric).

In its simplest form, a small hand-held probe connected to a flaw detector (oscilloscope) is coupled to the component surface. By scanning the probe and observing the response on the flaw detector screen (the A-scan display) the location of flaws can be determined and their size estimated. By suitable design of probe, ultrasonic beams can be introduced into the component material at almost any angle. Generally, a single probe acts as both transmitter and receiver of ultrasound, allowing inspection from one side of the component only (the single probe pulse-echo technique).

As well as this technique (the most common) there are many other techniques – tandem, through-transmission and Time of Flight Diffraction/TOFD (described in specialist NDT techniques Section 8.1.2). Most fine-grain metals can be ultrasonically tested, up-to large thicknesses, without difficulty. On the other hand, large-grain metals such as austenitic stainless steels are very difficult to inspect. Prior to their use ultrasonic systems require calibration.

With this method of testing, sensitivity to flaws can be very high. Considerable operator skill is required to interpret the A-scan displays. The majority of equipment is manually operated, however, for certain applications, complex multi-probe systems are used with computerised data acquisition/processing, display and analysis.

ii) Thickness Gauging

The determination of component thickness using thickness gauges is described here as it is the most common field application of the ultrasonic method of testing.

Thickness gauging is a manual operation which uses a small ultrasonic probe connected to a hand-held gauge. The main use of thickness gauging is to determine remaining wall thickness particularly in component areas where corrosion/erosion is suspected. For the assessment of component condition 'thickness surveys', as they are often referred to, are carried out. These are usually performed by making a number of 'spot' measurements with the thickness gauge in a grid pattern covering the component surface or the local area of concern.

While thickness gauging can provide an accurate measurement of component condition erroneous results can be reported. For example, spot

measurements will more than likely miss pitting. Another potential error source concerns the use of the gauge itself. Because the gauge only displays a digital thickness reading its use may be inappropriate in certain situations, for example, where the parent material may contain laminations/inclusions. Here an A-scan display from a conventional flaw detector will be required to identify the correct ultrasonic signal to be measured. Also, the presence of paint and similar coatings on the component surface can introduce significant errors adding several times their thickness to the total ultrasonic reading. (Note, as well as separate instruments which measure coating thickness, such as the 'Banana Gauge', special ultrasonic thickness gauges are now available which feature a separate sensor to measure coating thickness, this value being displayed by the gauge along with an accurate wall thickness reading).

Ultrasonic testing is one of the most powerful method of NDT available. With this method, detection of very small flaws and accurate sizing is possible. The capability of this method to accurately determine flaw size, in particular, flaw height, makes it an integral part of fitness-for-service assessment.

Limitations - High level of operator skill required to calibrate/operate equipment and to interpret signals/results. For manual testing (and to a lesser extent for automated testing), performance capability is heavily dependent on operator skill. Weld thicknesses $< \approx 5\text{mm}$ are difficult to test, as are coarse-grained structures such as those present in castings and austenitic stainless steel welds.

Typical Equipment Used:

- Ultrasonic Thickness Gauge or Ultrasonic Flaw Detector (oscilloscope type)
- Probes,
- Couplant
- Calibration Blocks
- Test Pieces

Relevant Personnel Certification:

- ◆ PCN: Personnel Certification is available at Levels 1, 2 and 3 (Welds, Castings and Wrought Products categories).
- ◆ CSWIP: Personnel Certification is available at Level 1 (Welds or Thickness Measurement categories) and at Levels 2 and 3 (Welds).

Relevant Standards:

- BS EN 1714:1998 - Ultrasonic Examination of Welded Joints (replaces BS 3923:Part 1:1986).
- BS EN 1713:1998 - Characterisation of Indications in Welds.
- BS EN 1712:1997 - Acceptance Levels/Welds.

- BS EN 10228-3:1998 - Ultrasonic Testing of Ferritic/Martensitic Steel Forgings (partially replaces BS 4124:1991).
- BS 4124:1991 - Ultrasonic Testing of Steel Forgings (partially replaced by BS EN 10228-3:1998).
- BS EN 12668-3:2000 - Non-destructive testing - Characterization and verification of ultrasonic examination equipment - Part 3: Combined equipment (replaces BS 4331:Part 1:1978).
- BS 5996:1993 - Ultrasonic Testing of Steel Plate.
- BS 6208:1990 - Ultrasonic Testing of Steel Castings.

Note: Further training courses and certification is available for the main NDT methods under the ASNT⁴ (SNT-TC-1A) scheme. Levels 1, 2, and 3 may be attained within this predominantly company-based scheme. In addition, the ASNT Central Certification Program (ACCP) is now available.

8.1.2. Specialist NDT Techniques

In this Section, some of the specialist NDT techniques are described.

a) Alternating Current Field Measurement (ACFM) Technique:

ACFM is an electromagnetic technique used for the detection and sizing of surface flaws in metallic components. The technique does not require any electrical contact with the surface of the component being inspected, and as such, can be used to inspect through coatings of various thickness and material. ACFM works by inducing a uniform electric current (AC) into the component; the presence of any surface flaw disturbs this uniform field, and measurement of the associated magnetic fields parallel to the flaw and perpendicular to the component surface allows flaw detection and sizing using specialist probes, instrumentation and software.

In its simplest form, ACFM involves the use of a single hand-held probe, which contains the field induction and the field measurement sensors. The probe is connected to an ACFM instrument, which is computer controlled, providing data display and recording. ACFM is usually deployed manually but can be automated. Probes with multi-element arrays for large area coverage are available as well as probes for high temperature applications.

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

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

⁴ ASNT (SNT-TC-1A) – American Society for Non-destructive Testing (Recommended Practice for establishing personnel training & certification programmes).

Probability of detection (POD) results obtained for ACFM indicate a similar performance to Magnetic Particle testing, but with fewer false calls.

b) Alternating Current Potential Drop (ACPD) Technique:

ACPD is an electrical resistance technique that can be used for the sizing of surface-breaking flaws in materials which are electrically conductive. ACPD works by applying an electrical potential between two contacts attached to the component surface and measurement of the difference in resistance between a second pair of contacts placed firstly across sound material adjacent to the flaw and then across the flaw itself. The increase in resistance due to the flaw is then directly proportional to the height of the flaw from the surface.

Whilst the ACPD technique is capable of accurate sizing, results are greatly affected by: (i) the length : height aspect ratio of the flaw - large aspect ratios giving the most accurate results, and (ii) the presence of conductive bridging material in the flaw which shortens the electrical path between the prods resulting in an underestimate of flaw height. ACPD equipment is portable and simple to use.

c) Ultrasonic Time of Flight Diffraction (TOFD) Technique:

TOFD is one of the specialist ultrasonic techniques now becoming widely used for the rapid detection and accurate sizing of flaws (flaw height). TOFD is a very sensitive two-probe technique that works by accurately measuring the arrival time of ultrasound diffracted from the upper and lower extremities of a flaw. Because TOFD relies upon diffraction from the flaw front for detection and sizing, flaw orientation is not an important consideration (as it is with the pulse-echo techniques that rely upon reflection).

With TOFD, best results are achieved with skilled operators and specialist equipment and software capable of generating high-resolution images of the component. A number of systems are commercially available. Scanning of the component can be performed in a variety of ways, from manual scanning with encoded positional feedback, for simple site applications, through to fully automated inspection for more hostile environments, scanning speeds of the order of 50mm/s are typical. TOFD is ideally suited to the following:

- Rapid 'screening' of simple weld geometries (probes placed either side of weld).
- 'Fingerprinting' of critical components.
- Critical assessment and sizing of flaws (accuracy for measurement of flaw height $\pm 1\text{mm}$ to $\pm 2.5\text{mm}$)*.
- Monitoring of flaw growth (accuracy for measurement of flaw growth of the order of $\pm 0.5\text{mm}$)**.

Whilst TOFD is a very powerful technique some limitations do exist. For example, dead zones exist under the scanning surface and at the back surface that can obscure

* Depends on particular test situation. Under laboratory-type conditions $\pm 1\text{mm}$ is very achievable. Under site conditions $\pm 2.5\text{mm}$ is more realistic.

** Requires tight control of test variables (between repeat inspections) to achieve this level of accuracy.

indications from a flaw thereby affecting detection and sizing performance. The depth of these zones is dependent on the probes and separation used for the inspection.

When used for weld screening, TOFD may not detect unfavourably orientated flaws such as transverse cracks. In addition, small flaws that are not serious can sometimes mimic more serious flaws such as cracks; because of this, characterisations based on TOFD alone should be treated with caution. When accurate flaw characterisation is needed, additional scanning using the pulse-echo technique will often be necessary.

d) Automated Ultrasonic Pulse-Echo Technique:

The most widely used ultrasonic technique is the pulse-echo technique. In order to enhance the reliability of this technique, specialist automated systems can be deployed. These systems facilitate single/multiple probe inspection and provide images of the component via sophisticated data collection, processing and analysis software.

In reliability terms, the main advantage of these systems, over the use of manual inspection, is that they remove the operator from the ‘front-end’ of the inspection thereby assuring full inspection coverage via pre-programmed manipulation and couplant monitoring. Another main advantage, over manual inspection, is the ability of automated systems to monitor component degradation via comparison of stored data/component images. Automated pulse-echo is ideally suited to the following:

- Weld inspection (using multiple probes)
- Corrosion Mapping/Monitoring (using a single probe)

Relatively new to the field of engineering inspection, but gaining acceptance, is Phased Array. With this pulse-echo technology it is possible to quickly vary the angle of the ultrasonic beam, to scan a component, without moving the probe itself - allowing multi-angle inspection from a single probe position. When applied to the inspection of welds, for example, a number of advantages are afforded:

- (i) Reduction in the number of probes/scans required (reduced inspection time)
- (ii) Increased coverage for restricted access areas
- (iii) Optimised inspection (using for e.g. different wave modes, beam focusing).
- (iv) Potentially easier interpretation of images of the component inspected.

With automated ultrasonic inspection, the collected data is usually presented in one or more of the following ways:

- **B-scan presentation:** the display of the results of ultrasonic examination showing a cross-section of the component. This presentation is normally associated with sizing of through-wall flaws. (This presentation can also apply to TOFD inspection).
- **C-scan presentation:** the display of the results of ultrasonic examination showing a plan-view of the component.

- **D-scan presentation:** the display of the results of ultrasonic examination showing a side-elevation, usually of a weld. This presentation is normally associated with the length sizing of flaws, and with the screening of welds using TOFD.

(Note, **A-scan presentation** is the display on an ultrasonic flaw detector used for manual inspection).

e) Ultrasonic Continuous Monitoring Technique:

Flexible mats/belts consisting of multi-element arrays of ultrasonic transducers are available for the continuous monitoring of the wall thickness of vessels and piping. These flexible devices, typically 50mm wide x 500mm long, are permanently bonded at specific locations to vessels and piping, providing a very accurate assessment of the corrosion rate via a PC based monitoring package. Alternatively a conventional ultrasonic flaw detector may be used with a data logger and switching device for connecting the various transducer elements in turn. These devices are useful where inspection by conventional means (e.g. manual ultrasonics) is difficult/impossible, for example, due to component geometry or hazardous inspection conditions.

f) Spark Testing Technique:

The high-voltage spark testing technique, or ‘holiday’ detection technique as it is often called, can be used to locate flaws in insulating coatings on conductive substrates. In combination with ultrasonics, for thickness measurement and the detection of de-laminations, spark testing is used to test the integrity of the welded joints of thermoplastic liners of glass reinforced plastic (GRP) storage tanks.

The technique works by applying a high-voltage to a suitable probe with an earth return connected to the conductive substrate (for lined GRP this substrate is included in the design of the joint). As the probe is passed over the surface of the coating a spark at the contact point and an audible alarm in the detector indicates a flaw. Spark testing equipment is portable and simple to use. A large variety of probes are available with selection dependent on the particular testing application.

Relevant Personnel Certification and Standards – Specialist NDT Techniques:

In general, for the specialist NDT techniques, there is little certification available and few standards covering their use.

For the ACFM & ACPD techniques, approved training courses and CSWIP certification at Levels 1 and 2 is available from at least one accredited training school. For the TOFD technique, training and certification under the ASNT (SNT-TC-1A) scheme is available from at least one accredited school.

In addition, for the TOFD technique, there are two available standards. One is a British Standard, BS 7706: 1993 – Guide to calibration and setting-up of the ultrasonic time of flight diffraction (TOFD) technique for the detection, location and sizing of flaws. The other is a European Pre-standard, ENV 583-6: 2000 – Non-destructive testing-ultrasonic examination - Part 6: Time-of-flight diffraction technique as a method for detection and sizing of discontinuities.

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

Material	NDT method			
	VT	PT	MT	ET
Ferritic Steel	✓	✓	✓	✓*
Austenitic Steel	✓	✓		✓*

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

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

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

Table 3 Detection and sizing capability of the main NDT methods

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

✓* Some Potential

Table 4 NDT method versus damage type

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

Table 4 (continued)

Damage type	NDT method/technique	Capability/limitations
Hydrogen Pressure Induced Cracking (HIC, Stepwise Cracking)	Ultrasonic Testing – External - 0° probe - 45° angle probe	Good detection at later stages, but there are no proven early warning (susceptibility to cracking) tests for on-site inspection.
Creep Damage	Surface Testing Ultrasonic Testing - Attenuation/loss of back wall echo - Backscatter - Velocity measurement	Magnetic measurements of Barkhausen noise, Differential Permeability or Coercivity are possible but also affected by other parameters e.g. stress and heat treatment. Surface Replication can be used to examine microstructure. Methods developed for detection of early stages have not been proven in the field. Standard ultrasonic testing techniques are suitable at later stages.
Fatigue Cracking (Internal/External)	Magnetic Particle Testing Penetrant Testing/Eddy Current Ultrasonic Testing/Angle Probe(s) ACFM (can be used in-lieu of surface techniques stated above)	Good detection capability but requires access to fatigue crack surface. Good length sizing capability. Some surface preparation usually required. As above, for non-magnetic materials. Good detection and sizing capability (length and <u>height</u>), enhanced by use of automated systems - TOFD gives very accurate flaw height measurement and allows in-service crack growth monitoring. Good detection capability but requires access to fatigue crack surface. Length and some depth sizing capability. Unlike Magnetic Particle does not usually require surface preparation and can be used through coatings. Better for inspecting welds than Eddy Current.
Stress Corrosion Cracking/SCC (Internal/External)	Surface Testing Ultrasonic Testing – External Acoustic Emission – External	Penetrant/Magnetic Particle (not austenitic)/Eddy Current (not ferritic) techniques - Good detection capability but access required to crack surface. Techniques require plant shutdown. Fair detection capability; can be used on-line. Specialist techniques have some capability to determine crack features (orientation and dimensions (inc. height)). On-line detection of growing SCC in large component systems too complex to be inspected by other techniques. Extraneous system noise can produce false indications.

8.2. REMOTE SCREENING TECHNIQUES

Remote screening techniques can be defined as those NDT techniques that are applied remotely from areas to be inspected. This contrasts with those where the probe(s) or scanner device is in intimate contact with the component surface and is searching for flaws directly under the probe(s) or in very close proximity.

In general, remote techniques tend to be rapid, economical methods for screening large areas of plant, or components, for the presence of structurally significant flaws. When flaws are detected, a localised inspection technique may be required to carry out a more detailed assessment to determine the size and nature of those flaws.

It should be noted that the use of remote screening techniques is not equivalent to 100% inspection with a localised inspection technique, since the latter generally has a higher probability of flaw detection. This is particularly important in critical situations where small flaws need to be detected with high reliability. In such situations, the more expensive option of providing full access for a localised inspection technique may be necessary.

Typical applications include:

- Inspection of thermally insulated pipes or vessels without the need to remove all the insulation.
- Inspection of lengths of buried pipe, road crossings, or under pipe clamps/supports. Situations where there is no local access to the pipe surface.
- Inspection of storage tank annular plates, which support the tank shell, without having to empty the tank and gain internal access.
- High-speed inspection of storage tank floors and carbon steel piping for hidden corrosion.

Some of the remote screening techniques, along with some of the local inspection techniques (Section 8.1), can be used for non-invasive inspection. Non-invasive inspection is a term commonly used for an inspection strategies that avoid the need to gain access to inspect the internal surfaces of a vessel or storage tank (see Section 7.8). Typical examples of non-invasive inspection techniques include:

- Automated ultrasonic techniques (e.g. TOFD to detect internal cracking or corrosion at welds in tanks/vessels see Section 8.1)
- Pulsed eddy current techniques to detect wall thinning through thermal insulation (see Section 8.2.3).

The capability of non-invasive inspection techniques has been investigated in a number of Group Sponsored Projects (GSP) managed by Mitsui Babcock Energy Limited (8.11-8.13). The projects have demonstrated the capability of various techniques to detect certain flaws in selected component/weld geometries. As

experience with these techniques is limited, there is still a need to demonstrate their capability for new applications.

GSP 6490 (1) concluded that ‘providing the non-invasive inspection techniques have been **technically justified**, i.e. their **capability demonstrated**, the application of these techniques can significantly reduce operating costs without compromising safety’. One of the ways in which their capability may be demonstrated is by agreement with previous invasive inspection results.

8.2.1. Thermography

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

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

Thermography has a wide range of applications; the most relevant important being the inspection of insulated pipework and vessels for potential corrosion under insulation (CUI) sites. Dependent on the temperature of the product contained these sites show up as either ‘hot’ or ‘cold’ spots on the heat picture due to the effect of moisture which increases local thermal conductivity.

However, in order to be able to detect these hot/cold spots there must be a temperature differential across the thickness of the component of at least 10°C. For some field applications, factors such as changes in surface emissivity, the affects of solar loading (sunlight heating the component) and atmospheric effects may need to be considered.

8.2.2. Long Range Ultrasonics

There are several systems that fall into this category, each with different capabilities and applications. All of these systems require operators with specific training and experience (in addition to basic ultrasonic qualifications), particularly for the process of data interpretation.

LORUS (RTD b.v.). This technique uses a special angle beam probe to direct a skipped beam of ultrasound up to one metre range. The probe is attached to a manual scanner with position encoding. Data is acquired by computerised ultrasonic pulse-echo equipment to produce colour-coded images of the area examined.

The technique is particularly applicable to the inspection of annular plates in storage tanks for corrosion damage. The probe is scanned on the accessible outer skirt of the annular plate, sending ultrasound into the inaccessible region. A limitation is that it is not possible to discriminate between top and bottom side corrosion and the scanning surface must be free of weld spatter, surface corrosion and loose scale or coatings.

CHIME (AEA Technology). This technique uses two ultrasonic probes spaced up to one metre apart. A combination of surface and bulk waves are transmitted between the two probes to carry out 100% volumetric inspection. Both probes are moved along parallel line scans to cover an area, and computerised equipment provides imaging facilities. For pipes up to 305mm diameter, complete circumferential coverage can be achieved in one scan. In order to obtain two dimensions of flaw area, probes must be scanned in both longitudinal and circumferential directions.

The technique is particularly applicable to inspection for corrosion under pipe supports or clamps. As with most ultrasonic techniques, the scanned surfaces must be smooth, free from weld spatter, loose scale or coatings.

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

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

8.2.3. Pulsed Eddy Current

INCOTEST (RTD b.v.), PEC (Shell Global Solutions). These systems monitor the decay of an eddy current pulse within a ferritic steel pipe or vessel and use these signals to calculate the average remaining wall thickness beneath a coil unit. They can be applied through thermal insulation up to approximately 100mm thickness including a non-magnetic metallic cladding or mesh (i.e. stainless steel or aluminium). The technique is most sensitive to general metal loss and areas of localised corrosion/erosion.

A limitation is that these systems cannot differentiate between internal and external metal loss and are not able to detect small (but possibly deep) isolated pits due to the large size of the coil unit ‘footprint’.

8.2.4. Real-time Radiographic Imaging

SENTINEL (Amersham QSA). This system utilises a hand-held image intensifier coupled to a low energy Gadolinium radiation source. The method of inspection is to move the hand held unit around the pipe circumference such that 100% coverage of the pipe external surface is obtained. The radiosopic image is viewed on a monitor or helmet mounted real-time display.

It is applicable to piping with thermal insulation to detect the presence of corrosion under insulation (CUI). The radiation is projected through the thermal insulation, at a tangent to the pipe wall, to the image intensifier such that corrosion pits are seen in profile on the real-time display.

8.2.5. Neutron Backscatter

The neutron backscatter technique is a screening technique which can be used for the inspection of insulated pipework and vessels to locate areas of wet insulation, which are potential corrosion under insulation (CUI) sites.

Neutron backscatter devices ('hydrodetectors') work by emitting fast (high-energy) neutrons into the insulation from a neutron source. These neutrons are slowed down after collision with hydrogen nuclei in the areas of wet insulation. A detector, sensitive to slow (low-energy) neutrons, then counts the slow neutrons that are backscattered. Low counts per time period mean low moisture whilst high counts per time period mean high moisture i.e. an area of wet insulation.

Devices typically consist of a neutron source and detector assembly on the end of a telescopic pole. This allows access to hard-to-reach areas of pipework and vessels. Typical screening rates are the order of 300m of insulated pipework per day.

8.2.6. Acoustic Emission

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

When compared to a previous test, the amplitude of the received signals can give an indication of the rate of growth of the defect. AE is often used in conjunction with the initial hydrostatic pressure testing of vessels or piping. AE has also been used to monitor atmospheric storage tanks (without application of additional stress), listening for corrosion product fracture.

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

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

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

8.2.7. Magnetic Flux Leakage

Magnetic flux leakage (MFL) is only applicable to ferromagnetic materials. The component is magnetised, and, depending on the level of induced flux density, magnetic flux leakage due to both near and far surface flaws is detected by the voltage induced in a detector coil, or Hall-effect sensor, traversed over the surface of the component. Unlike MPI, the method is not limited to surface breaking or near-surface flaws, but actually becomes increasingly sensitive to far surface flaws with increasing levels of magnetisation. The output from the detector can be amplified, filtered, digitised, stored etc. to produce an automated inspection system. Multiple-element and differential probes are also used, and inspection speeds can be very high.

MFL is finding increasing use in the petrochemical industry for providing high-speed inspections of storage tank floors and carbon steel piping. These systems use either permanent or electromagnets to provide localised near-magnetic saturation coupled with induction coil or Hall-effect sensor arrays for detecting anomalous flux leakage caused by corrosion defects (both near as well as far surface). Many of these systems rely upon the use of an adjustable threshold, or amplitude gate, for detection of corrosion in real-time. Some more advanced systems, through the use of computerised equipment with signal processing, provide corrosion maps of inspected areas similar to the C-scan presentation of ultrasonic data.

8.3. ASSESSMENT OF INSPECTION PERFORMANCE AND RELIABILITY

The normal process of inspection aims:

- To detect and locate areas of deterioration or flaws of concern.
- To determine their extent by providing flaw dimensions.
- To determine the type, or character, of flaws.

Inspection performance may be defined as the ultimate capabilities of an NDT technique to detect, size and determine the type of a flaw in a given component. Inspection reliability is a statistical measure of the expected variability in inspection performance in many applications of the technique.

The performance and reliability of inspection by NDT can be expressed by data of different kinds. An important division is data representing flaw detection performance and data representing the accuracy of flaw measurement. These two aspects are described in the following sections.

8.3.1. Flaw Detection Performance

Two methods typically used to present flaw detection performance are:

- Probability of Detection.
- Relative Operating Characteristic.

Note that Probability of Detection is used more often than the Relative Operating Characteristic. The following sections describe these two methods.

a) Probability of Detection:

Probability of Detection (POD) is normally plotted against an appropriate flaw parameter, e.g. flaw length or flaw height, as shown in Fig. 8.1. This presentation is particularly suited to NDT methods that provide a hit/miss result, e.g. detection of surface breaking cracks by MPI. POD trials are conducted on a large number of samples having a predetermined number of flaws in each chosen size range.

The number of detection successes in each size range is used to determine an experimental point on the graph. From these experimental POD results, based on a limited number of flaw samples, conventional binomial statistical procedures may be used to calculate the lower bound 95% confidence limit. Typically a minimum sample size of 29 flaws of each size range is chosen, such that when all flaws are detected, a 90% POD at a lower bound 95% confidence limit is demonstrated. The method of conducting trials and constructing POD curves is documented in an ASNT Recommended Practice (8.1).

The results of POD trials can be heavily influenced by the population of flaws used, such as their type, the number and spread of flaws in each size range and other variables such as the minimum depth threshold for detection (for surface flaws).

b) Relative Operating Characteristic:

The Relative Operating Characteristic (ROC) presentation takes account of the fact that NDT measurements are made in the presence of noise. This can be 'electronic' noise which is readily reduced by filtering and averaging, or more significantly 'component' noise generated by sources such as surface roughness, grain structure and geometry variations. The flaw signal-to-noise ratio is a primary factor in determining the level of discrimination for a given NDT procedure. The probabilities of the four possible outcomes from an inspection procedure can be expressed simply as:

- Probability of true detection (POD) - a flaw exists and one is reported.
- Probability of false alarm (PFA) - no flaw exists but one is reported.
- Probability of false non-detection - a flaw exists but none is reported.
- Probability of true non-detection - no flaw exists and none is reported.

Because of the interdependence of these four probabilities, only two need to be considered to quantify the inspection task, these are POD and PFA. These data may be used to construct a ROC curve as shown in Fig. 8.2. The solid line is generated by the locus of points obtained from a group of flaws having the desired level of discrimination (similar signal to noise ratio). High performance will result in a high POD and low PFA, which means points at the upper left-hand corner of the graph.

The ROC method (8.2) has been used to quantify the proficiency of operator performance by having a number of test specimens containing flaws of a similar size evaluated by an operator using a specific NDT procedure. The result is used to generate a single point on the ROC curve. The procedure is repeated for several operators. The performance of the best operators should fall near the upper left-hand corner of the graph and a zone of acceptable performance can be selected. Operators whose performance lies outside this zone are less proficient and require further training.

8.3.2. Flaw Measurement Accuracy

It is important to note that inspection techniques used for flaw measurement may be different to inspection methods used for the detection of flaws. The selection of appropriate flaw measurement techniques may depend on the requirements of the applicable flaw acceptance standard. The latter may either be based on weld quality control or 'good workmanship' criteria, or they could be based on fracture mechanics or 'fitness-for-service' criteria. In either case, the inspection methods selected must be capable of providing the required flaw information.

The range of flaw measurement information that may be required can be summarised as follows:

- Flaw location. This is determined with respect to a datum (0) position and is typically specified in terms of a 3 co-ordinate system (e.g. x, y, and z). These co-ordinates may be aligned with the axes and surfaces of a component e.g. a plate or pipe, or in the case of a weldment, the principal weld directions. It is also important to specify whether the location is measured to the start i.e. the closest point of a flaw, or to the centre of a flaw.
- Flaw length. This is measured with respect to a defined direction, for example, along the longitudinal axis of a pipe, or in the case of a weldment, in the primary weld direction.
- Flaw width. This is measured with respect to a defined direction, for example, in the circumferential direction around a pipe, or in the case of a weldment, transverse to the primary weld direction.
- Flaw height. This is measured with respect to a defined direction, for example, normal to the plate, pipe or weld surface.
- Flaw orientation. In some situations it may be necessary to determine the orientation of flaws, particularly for planar flaws. This is normally defined in

terms of a flaw skew and tilt angle with respect to a particular reference plane. In the case of a weldment, the reference plane would be typically aligned with the weld centreline.

Two methods typically used for presenting flaw measurement accuracy are:

- Mean position and sizing errors/standard deviations.
- Measured response versus actual flaw size (\hat{a} versus a).

i) Mean Position and Sizing Errors:

Numerous studies have been carried out to quantify the errors and uncertainties for particular flaw measurement techniques. The results are typically expressed in tabular form and provide values for a mean sizing error together with a standard deviation of the errors. Note that two-sided 95 % confidence limits are expressed by the mean error \pm two standard deviations.

Studies that have quantified flaw size measurement accuracy include a programme carried out by the CEGB and its successor Nuclear Electric on ‘The assessment of defect measurement errors in the ultrasonic NDE of welds’ (8.3, 8.4). This study provided guidance for NDT operators to combine estimated calibration and measurement errors into an overall sizing error with a specified confidence level. The latter recommended two styles of reporting flaw size and the associated estimate of sizing error:

- Best estimate $10\text{mm} \pm 2\text{mm}$ at 80% two-sided confidence.
- Upper bound estimate 12mm at 90% one-sided confidence (random error of $\pm 2\text{mm}$ allowed for).

Further, an IIW guidance document ‘Assessment of the fitness-for-purpose of welded structures’ (8.5) provides, in an appendix, estimates for all major NDT techniques of the smallest flaws that can be detected and the typical measurement accuracy’s. The document also recognises that sizing uncertainties should ideally be expressed with associated statistical confidence limits, although none are actually provided.

ii) Measured Response versus Actual Flaw Size:

Response versus size graphs (also known as \hat{a} versus a) are ideally a plot of log (measured flaw size or response) versus log (actual flaw size) as shown in Fig. 8.3. This method of data presentation is particularly suited to NDT methods that produce an output signal which can be correlated to flaw size, e.g. echo amplitude in ultrasonic testing or peak voltage in eddy current testing. The inspection results from a number of samples containing flaws of known sizes are plotted and values determined for the slope and intercept of a straight line fit to the data. The residuals are often found to be normally distributed about this line and the variance of the residuals is usually assumed to be independent of flaw size.

8.3.3. Discussion of POD and Flaw Measurements

In practice, the probability of detection of flaws is influenced by many factors. The use of several complementary NDT techniques can increase the overall POD, i.e. by applying the strategy of redundancy and diversity. However, when considering a single NDT technique, the factors influencing the POD may be listed as follows:

- **Technique factors:** the intrinsic detection capability of the technique/procedure adopted and the number of separate scans or tests carried out.
- **Component factors:** the component geometry, surface conditions, the material types, grain structure and thicknesses, the available access for inspection.
- **Flaw factors:** the flaw type, size, position and orientations of concern.
- **Human factors:** the inspector competence, the environment and time constraints.

Clearly, these factors need to be taken into consideration when determining how appropriate POD values obtained from inspection trials data are to the real situation.

All flaw measurements are subject to errors and uncertainties. Sizing errors are systematic, i.e. intrinsic to the measurement technique, resulting in general tendency to either oversize, or undersize, a flaw. They are defined by a value for the mean error. Sizing uncertainties are random, and can be thought of as the variations resulting from repeat measurements by the same or different inspectors. They are defined by a value for the standard deviation of the errors.

In practice, it may be difficult for the NDT inspectors to provide reliable estimates for the errors and uncertainties in flaw size measurement. This may be because these are not well understood or because they can vary depending on the inspection technique, component geometry, flaw position etc. Mean error values are rarely provided in practice; often the best that is available is an estimate for the overall random uncertainty, without any statistical qualification.

The choice of an appropriate flaw measurement technique depends on the requirements of the applicable flaw acceptance standard. In situations where weld quality control or ‘good workmanship’ based criteria are being applied, there may be less onerous requirements than in situations where fracture mechanics or “fitness-for-service” based criteria are applied. In the first case, it may only be required to determine the flaw length (and type), whilst in the second case, a complete assessment of the flaw position and dimensions (with a high level of measurement accuracy) may be required.

In addition to the flaw measurements, it is often necessary to determine the flaw type, or character. Flaw acceptance standards based on good workmanship criteria often require the flaw type to be identified precisely, i.e. cracks, lack of fusion, gas pores, solid inclusions etc. Exceptions to this are specially adapted criteria for ultrasonic testing which specify flaw types based on the indication responses, i.e. planar surface, planar embedded, threadlike, volumetric, isolated, multiple

indications etc. For flaw acceptance based on fitness-for-service criteria it is often only necessary to determine whether the flaw is planar, or non-planar, in nature and its orientation.

Two recent programmes which have examined detection and flaw sizing performance for corrosion defects in piping and in-service flaws in welds are: The Reliability Assessment for Containers of Hazardous Material (RACH) project (8.6) and the Programme for Assessment of NDT in Industry (PANI) (8.7).

RACH was funded via the EC THERMIE programme with additional support from the HSE and industry. It carried out blind trials to determine POD and sizing accuracy for a range of new and established NDT techniques applicable to detection of corrosion damage in pipes and vessels. The results were combined with damage modelling and quantitative reliability assessment to provide a rational basis for inspection scheduling.

The PANI programme was funded by the HSE to investigate the performance of the in-service NDT used for the inspection of industrial plant components. Manual ultrasonic testing was selected as the NDT method to be investigated by application of a number of test pieces in a round-robin exercise. The test pieces contained in-service defect simulations and were mounted to represent on-site access conditions. An ex-service boiler, containing unacceptable defects, was also included in the population of test pieces. Many of the UK's leading inspection companies participated. The results of the PANI programme showed a wide variation in defect detection and sizing performance.

The PANI programme has led to the publication of a HSE document (8.8) 'Best Practice for the Procurement and Conduct of Non-Destructive Testing, Part 1: Manual Ultrasonic Inspection'. The aim of this document is to improve the specification of inspection of conventional pressurised equipment.

8.4. INSPECTION QUALIFICATION

8.4.1. Introduction

Inspection Qualification, sometimes referred to as Inspection Validation or Performance Demonstration, is a systematic assessment of an inspection (the procedure, including equipment, and personnel) to ensure that it is capable of achieving the required performance under realistic conditions. Inspection Qualification is applicable when:

- a) The safety and/or economic consequences of inadequate inspection are severe.
- b) The inspection method(s)/technique(s) being applied is new/sophisticated (not covered by existing standards or certification arrangements).
- c) Inspection is likely to be problematic, as a result of complex component geometry/difficult to inspect material(s).

Inspection Qualification involves the compilation of theoretical information and practical data, the main elements of which are:

- a) A Technical Justification, and
- b) A Practical Assessment (carried out using a representative test piece(s))

Two documents are in existence that can be used as a basis for the development of inspection qualification programmes. One is a European document (8.9) developed by ENIQ, the European Network for Inspection Qualification. This document is widely used within the nuclear industry both in the UK and in Europe. The other is a BSI document (8.10) that used the ENIQ document as a basis for its development. This document is aimed at the non-nuclear industry.

8.4.2. Technical Justification

A Technical Justification is a collection of information that provides evidence of inspection capability. The Technical Justification might include physical reasoning (inc. identification and discussion of the essential parameters of the inspection), mathematical modelling and inspection results.

The Technical Justification should identify 'worst-case' defects, i.e. defects judged to be the most difficult to detect and size at specific locations.

8.4.3. Practical Assessment

A Practical Assessment involves the conduct of trials on a test piece(s) representative of the component, and provides a demonstration of inspection capability. Material composition, size/geometry and the defective condition of the component should be represented. The population of the test piece(s) should include 'worst-case' defects.

Test piece trials to prove the capability of the inspection procedure should normally be carried out 'open', i.e. the personnel involved in the trials having specific knowledge of the defects contained in the test piece(s).

Test piece trials to assess the capability of the inspection personnel, to apply the proven procedures correctly under realistic conditions, should normally be carried out 'blind', i.e. the personnel involved in the trials having no specific knowledge of the defects contained in the test piece(s).

The combination of theoretical evidence and practical demonstration provides powerful confirmation that the inspection is capable of achieving the required performance. The mix of the two depends on the inspection being qualified and the level of qualification (see Section 8.4.4). In general, the more straightforward the inspection the more practically biased the mix; the more complicated the inspection the more equal the mix.

8.4.4. Qualification Level

The level of rigour is a matter to be agreed between the different parties involved (plant owner/operator, regulatory body etc). More often than not, the safety and/or economic consequences of component failure are the major factors in determining the level of rigour required.

recommended. In particularly difficult and important inspections, it may be beneficial for more than one operator to carry out the same inspection.

NDT method/technique selection should be based on the capability to detect and assess the deterioration types anticipated/sought in the parts of interest. The Duty Holder and/or Competent Person should have evidence of this capability, together with knowledge of any significant limitations.

For established techniques, satisfactory evidence may be available through published literature. Additional confidence is provided by inspection procedures that are produced in accordance with national codes and standards. For newer or more specialised techniques, where the only available evidence may be capability data provided by the equipment supplier, an independent assessment of the capabilities and limitations may be necessary.

An important issue is whether the magnitude of the risk justifies the need for inspection qualification. In situations where the full process of qualification (requiring pass/fail criteria) is not considered necessary, the provision of capability statement(s) should be considered as a suitable alternative. In lower risk situations inspection qualification is not generally necessary.

Continuity of inspections and inspection data is important. A key part of the RBI process is the feedback of knowledge of plant condition into the inspection planning process. Thus, attention should be paid to how records of inspections carried out, and the results, are kept and archived.

8.6. SUMMARY OF MAIN POINTS

- a) The performance and reliability of the inspection and NDT needs to be commensurate with the risk of failure of the components/equipment inspected.
- b) Inspection procedures should be available that cover the whole range of plant components/weld geometries to be examined.
- c) NDT methods/techniques must be selected that are appropriate for the detection and assessment of the types of deterioration anticipated/sought and the characteristics (e.g. location, orientation etc.) The size of flaw for which reliable detection is required may be based on existing acceptance standards or fitness-for-service calculations.
- d) Personnel involved in inspection and NDT must be competent and have the appropriate training and qualifications for the tasks to be carried out.
- e) Inspection equipment should be checked before use to ensure that it is functioning and calibrated correctly.
- f) When high inspection performance and reliability is required, a number of complementary NDT techniques should be selected on the principles of diversity and redundancy.

- g) For high-risk components, inspection qualification is beneficial in order to ensure high confidence in the inspection results.
- h) Duty Holders should have evidence of the capability of NDT techniques by (in order of preference):
 - (i) Referring to independent published capability data,
 - (ii) Carrying out their own capability assessment,
 - (iii) Obtaining capability statements from equipment manufacturers.

Capability assessment should be a requirement for new or specialised inspection techniques (particularly for non-invasive, long range, or remote techniques) where these are being used in situations where prior evidence and experience of capability is not available.

- i) In order to enable an accurate assessment of component deterioration, the inspection results should be compatible with those from previous inspections. This is important if the inspection technique being proposed differs significantly from the technique(s) used for previous inspections.
- j) Inspection datums and co-ordinate systems marked on components being examined should be kept for future inspections.
- k) Inspection results should be archived using an appropriate method.

8.7. REFERENCES FROM CHAPTER 8

8.1 ASNT Aerospace Committee: 'Recommended Practice for a Demonstration of Non-destructive Evaluation (NDE) Reliability on Aircraft Production Parts'. Materials Evaluation Vol. 40, August 1982, 922-932.

8.2 Rummel WD, Hardy GL and Cooper TD: 'Applications of NDE Reliability to Systems'. Metals Handbook 9th Ed Vol. 17, ASM Int. 1989, 674-688.

8.3 Chapman RK: 'CEGB Guidance Document on the Assessment of Defect Measurement Errors in the Ultrasonic NDT of Welds'. Proc 27th Ann Brit Conf NDT, Portsmouth, 1988, Brit Inst NDT, 173-185.

8.4 Chapman RK: 'Guidance Document on the Assessment of Defect Measurement Errors in the Ultrasonic NDT of Welds'. Nuclear Electric Technology Division Report TIGT/REP/0031/93, 1993.

8.5 IIW/IIS-SST-1157-90: 'Guidance on assessment of the fitness-for-purpose of welded structures', Int. Inst. of Welding, 1990.

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- 8.7 HSE Project: 'Programme for the Assessment of NDT in Industry (PANI)'. Work managed by AEA Technology. 1997-1999.
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- 8.9 EUR 17299 EN, Second Issue (1997) - European Methodology for Qualification (document prepared by European Network for Inspection Qualification (ENIQ)).
- 8.10 98/711582 (1998) - Methodology for Qualification of Non-Destructive Tests (document prepared by Panel WEE/46/-/9 of BSI).
- 8.11 Mitsui Babcock Energy Ltd. Group Sponsored Project 6490: 'Periodic inspection of vessels from the outside only'. 1995.
- 8.12 Mitsui Babcock Energy Ltd. Group Sponsored Project 6748: 'Non invasive inspection within an asset risk management strategy'. 1996-1998.
- 8.13 Mitsui Babcock Energy Ltd. Group Sponsored Project 235: 'Recommended practice for non-invasive inspections'. 1999-2001.

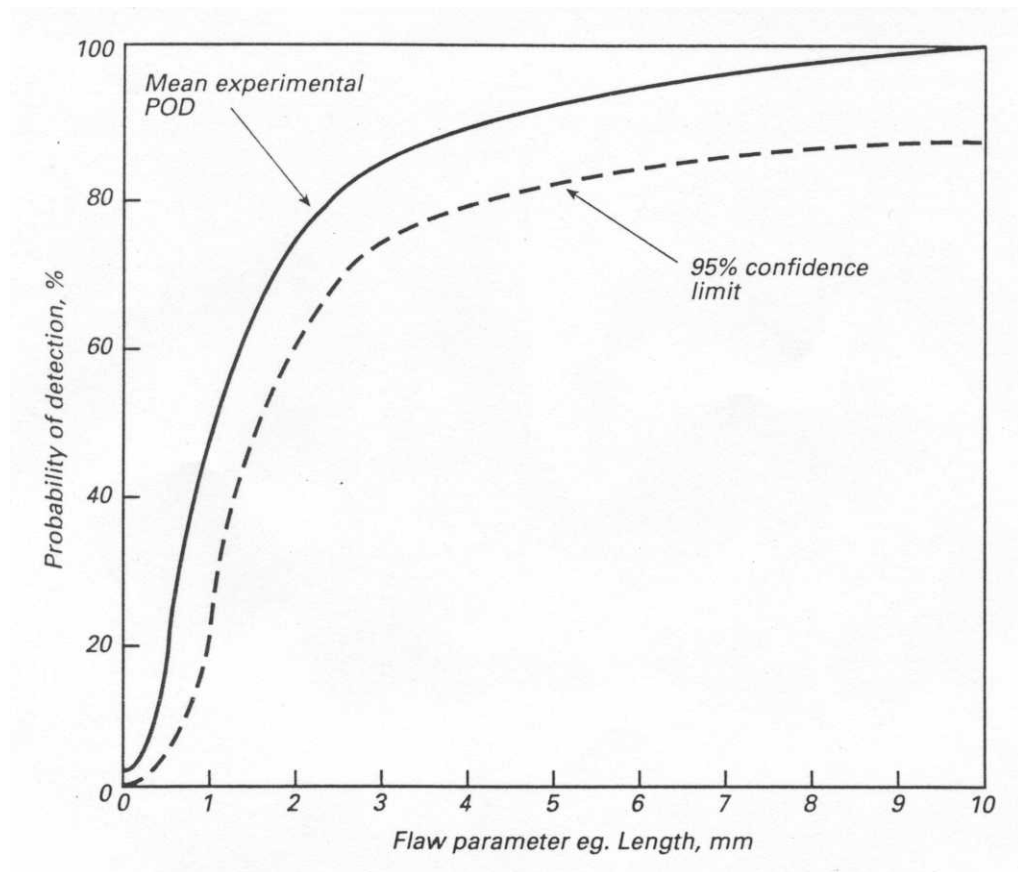


Fig. 8.1 Example of probability of detection (POD) versus flaw size data presentation

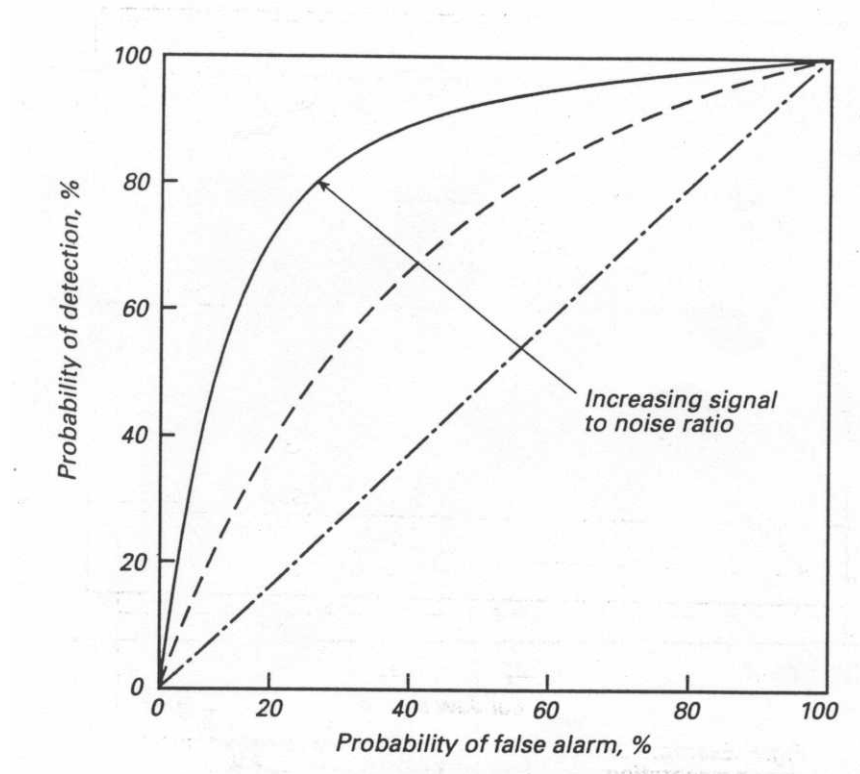


Fig. 8.2 Example of Receiver Operating Characteristic (ROC) data presentation

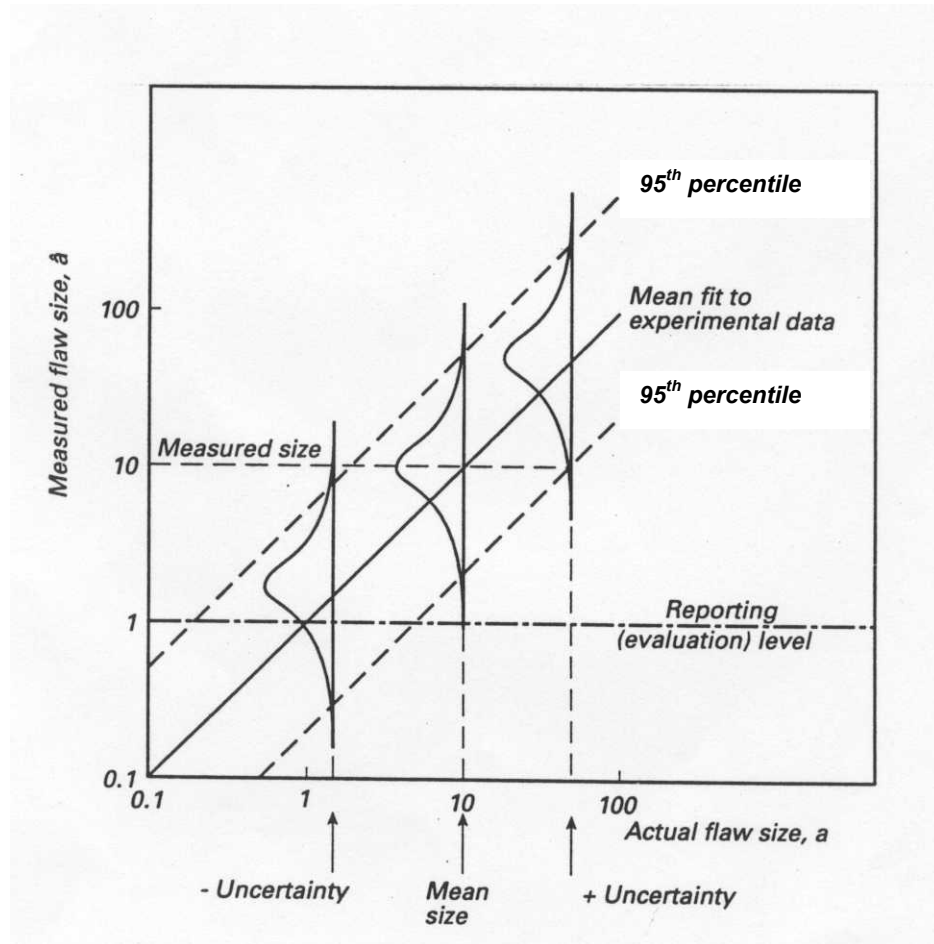


Fig. 8.3 Example of measured response versus actual flaw size data presentation

9. FEEDBACK FROM RISK BASED INSPECTION

9.1. FITNESS FOR SERVICE ASSESSMENT

The Competent Person carrying out the examination of a system will evaluate the examination results and the condition of the equipment. Any changes in the condition from the design, since entry to service, and since the last inspection will be identified. From this and other information about the rate of deterioration, the Competent Person will assess whether the system is currently ‘fit-for-service’ and likely to remain so during the proposed interval to the next inspection.

When faced with evidence of deterioration, the Duty Holder and Competent Person will need to assess the implications of the deterioration in more detail and decide what action should be taken. In making these assessments, risk based principles should apply. Initial considerations towards a decision to accept or reject the deterioration (i.e. corrosion, erosion or crack like defects etc) within the equipment will need to take into account the following:

- The type and magnitude of the deterioration, its cause and mechanism, and the accuracy of the NDT information available.
- The stress at the location which is affected, i.e. high stressed by areas are unlikely to tolerate the same degree of deterioration as other areas operating at lower levels of stress.
- The type of material, its strength and fracture properties over the range of operating temperature.
- The safe operating limits associated with each operating condition. These must be considered separately, e.g. a certain corrosion type defect may be acceptable under an operating condition where only pressure is considered. However, should a cyclic operating condition apply then the defect may not be acceptable. Care must be exercised when there are different operating conditions.
- Whether the deterioration has been present since entry to service, or has initiated during service (due to the contents, environment or operating conditions), and the rate at which it is proceeding.
- Whether the deterioration is within design allowances (e.g. for corrosion) or fabrication quality control levels (e.g. for defects).

Even if defects more severe than fabrication ‘quality control levels’ are revealed by an examination, rejection or repair of the equipment may not always be necessary. Quality control levels are, of necessity, both general and usually very conservative. A decision on whether to reject or accept equipment with defects may be made on the basis of an ‘engineering critical assessment (ECA)’ using fracture mechanics to assess the criticality of the defects. This may be carried out using before or after the examination.

British Standard 7910 (9.1) provides a 'Guide on methods for assessing the acceptability of flaws in metallic structures'. It is based on the concept of fitness-for-service and utilises a failure assessment diagram (FAD) derived from fracture mechanics. The assessment process positions the flaw within acceptable or unacceptable regions of the FAD.

The flaw lying within the acceptable region of the FAD does not by itself infer an easily quantifiable margin of safety or probability of failure. Conservative input data to the fracture mechanics calculations are necessary to place reliance on the result. If key data are unavailable, (e.g. fracture toughness properties of the weld and parent material), then conservative assumptions should be made. Sensitivity studies are recommended so that the effect of each assumption can be tested.

Flaw assessment is a process to which risk based principles may apply. Degrees of uncertainty in the input data (e.g. flaw dimensions, stress, fracture toughness) may be handled in a lower bound deterministic calculation or by probabilistic fracture mechanics if statistical distributions can be determined. The application of partial safety factors is an alternative approach to manage the variability in the input data without being overly conservative. The consequences of flaw growth and the possibility of leakage or catastrophic failure may also be factors to consider.

BS 7910 was developed from BSI Published Document PD 6493, which provided guidance on methods for assessing the acceptability of flaws in fusion welded structures. Duty Holders should also be aware of the R6 methodology (9.2), originally developed by the CEBG for application to nuclear and conventional power plant, and ASME XI for the assessment of results from in-service inspection of nuclear plant designed to ASME codes. For refinery equipment designed to ASME codes, the American Petroleum Institute has published a recommended practice on fitness for service assessment, API 579 (9.3).

If deterioration is found in equipment, the best course of action for the Duty Holder will depend on the circumstances. Equipment that has deteriorated to a condition assessed to be unacceptable requires immediate action before it can re-enter service. Where equipment has deteriorated but has not reached unacceptable limits, monitoring or shorter inspection intervals or other action may be required depending on the rate at which the deterioration is proceeding, and the confidence with which this rate is known.

In practice, the Duty Holder will normally choose the most economical course of action, whilst maintaining the integrity and safety of the equipment. Duty Holders often prefer to return equipment to service and plan repairs or replacements for scheduled outages. Various alternatives can be considered:

- Changes to the operating conditions that reduce the rate of deterioration and increase margins of safety, e.g. lower pressures, temperatures.
- On-line monitoring of deterioration.
- Shortening the interval between subsequent inspections.
- Removal of defects or damage (e.g. grinding).
- Removal of defects or damage and making a repair.

9.2. RISK OF REPAIRS AND MODIFICATIONS

When repairs or modifications are made to established systems, there are particular risks that the work will in fact increase the likelihood of failure. An extreme example was the Flixborough accident where the design of a temporary modification failed to take the system loads into account. Weld repairs can be a source of deterioration from defects, poor material properties, and high residual stress if inappropriate procedures and heat treatment are used.

Duty Holders should therefore be aware of the risks of repairs and modifications and take appropriate steps to manage these risks. The technical and quality standards for repairs and modifications should be at least as good, and preferably better, than the original standards of the item of plant. The Pressure Systems Safety Regulations 2000 (PSSR) (9.4) state that when designing any such work the following should be taken into account:

- The original design specification and code requirements.
- The future duty for which the system is to be used after the work.
- The effects such work may have on the integrity of whole system.
- Whether the protective devices are still adequate.
- The continued suitability of the written scheme of examination.

Under the guidance to Regulation 13 of the PSSR, the User should consult a Competent Person for advice before work begins on any substantial modification or repair which might increase the risk of system failure. The Competent Person has responsibility to ensure that repairs or modifications are properly designed and are carried out in accordance with appropriate standards. He/she must also ensure that the integrity of the system or operation of any protective device is not adversely affected whenever repairs or modifications are made to pressure retaining and non-pressure retaining parts of a system.

It is good practice for the Competent Person to review the continued suitability of the written scheme of examination for the system at the time when any repairs or modifications are made. This review will ensure that the scheme is revised, if necessary, to take account of the repairs or modifications. Feedback from experience that might affect the scope, frequency, and nature of future examinations of other parts of the system can also be incorporated.

It should be considered good practice for the written scheme of examination to be reviewed, at the time of any repair or modification, by a Competent Person. This review will ensure that the scheme remains valid and that feedback from the repair or modification can be taken into account in establishing the nature, scope, extent or frequency of any future in-service inspection.

All information relating to the repair or modification should be included in the plant database and be available to the RBI team for review. This information should include, as a minimum, drawings, calculations, material certification, weld procedures and details of reasons for repair or modification (if applicable).

9.3. RISK RE-ASSESSMENT FOLLOWING EXAMINATION

Following the examination and assessment of the results and fitness-for-service, the RBI team should meet and review the new information obtained from the examination and re-assess the risk of failure. The effect of any repairs made to the equipment, or proposed changes to any of the operating conditions, should be taken into account.

The RBI team should address whether the condition of the equipment was better, or worse, or the same as was estimated from the risk assessment. In particular, the team should review whether the effect of specific actions taken as a result of the previous inspection and risk assessments (e.g. changes to operating conditions), have been as intended.

The risk assessment process will have been effective if the condition is as estimated and the effects of actions as intended. If the condition differs significantly from what was estimated, either much better or worse, then the risk should be re-assessed. Previous actions may need to be reviewed and modified accordingly.

Evidence of the re-assessment of risk after examination should be available and indicate where the assessment has changed. Possible outcomes are:

- The assumptions made were reasonably conservative, so no adjustments to the initial risk assessment are necessary.
- The assumptions were not sufficiently conservative or a new, or unanticipated, deterioration mechanism is identified.
- The assumptions were significantly over conservative, and data suggest re-assessment might yield a lower risk ranking on the next pass. It may be prudent, but not necessary, to reassess under this circumstance.
- Some combination of the above outcomes.

The RBI team will need to consider if the examination that has been carried out was sufficient and appropriate in the light of the information and data gathered. Evidence of unanticipated deterioration may indicate that a wider examination and/or the use of different NDT methods is necessary. The assumptions of the risk assessment may need to be reviewed and the risks from equipment experiencing similar conditions re-assessed with the benefit of improved knowledge.

During the re-assessment, it is essential to review previous inspection procedures and plans. It is important to develop the written scheme of examination to take account of experience. This should be a structured and documented process.

It has been common practice for written schemes of examination to be produced on a generic basis. The scope and extent of any non-destructive inspection is left to the discretion of the Competent Person carrying out the inspection. This does not lend itself to producing a scope of inspection that is clearly defined on the basis of a risk based assessment.

It is considered best practice if the risk re-assessment process is identified within the written scheme of examination and forms an integral part of the inspection. This would provide a means to drive and control the process. The scheme could also state conditions where re-assessment and re-appraisal of the written scheme was required at other times (see Section 9.6).

New data may effect the risk analysis and risk ranking for the future. After inspection, repairs or change removal of the adverse environment, the risk for an item of equipment may be re-assessed to be significantly lower. This might move it down the risk ranking and allow the future inspection plans to be revised to focus on other items of equipment.

9.4. UPDATING THE PLANT DATABASE

Duty Holders have a responsibility to update the plant database following each examination and any repairs, modifications or replacements to the plant or changes in operating conditions. This will form the basis for the next risk assessment. Recording examination results is a requirement under the PSSR (9.4) and a general requirement to update the plant database base after each examination should be included within organisations' quality procedures.

The state of plant knowledge can change due to a variety of reasons, such as the result of examination, engineering evaluation and corrective action, accumulated service experience, maintenance and repair activities. Other sources, such as industry databases and professional contacts, may also provide new relevant information. New knowledge and information can change the estimates of the probability or the consequence of failure, even if the plant has not physically changed.

Most plants, regardless of the industry, do change over time. Equipment is often replaced, because of degradation, to improve production, to increase reliability, to ease the work of operators or for many other reasons. Sometimes old equipment is used under different operating conditions than for which it was originally designed, different working fluids, different throughputs etc. Changes in the physical plant or changes in the process usually trigger a need to update the plant database.

As knowledge is gained from inspection and testing, then uncertainty may be reduced but not eliminated. The whole process can never be considered complete and the continued management of the risks throughout the life of the plant is essential. The input data to the risk assessment should therefore be reviewed on a regular basis.

9.5. REMAINING UNCERTAINTY

During the risk assessment process, conservative assumptions may need to be made about factors affecting the probability of failure because of insufficient data. This is also the case when there is uncertainty about the nature and scale of the consequences. The purpose of plant integrity management and risk based inspection, is to manage uncertainty safely and to improve the data.

Uncertainty will always be present, mainly because issues are ambiguous, and because of the intrinsic limits of human knowledge, activity and measurement systems. The RBI assessment team should be aware of where there is uncertainty and the potential for unreliability. A well-recognised weakness of risk assessment is that the initial identification of the potential hazards may be incomplete.

Uncertainty can occur in many forms, with each affecting the risk assessment in a different way.

Knowledge uncertainty arises when knowledge is represented by data based on too few statistics. It can be managed by deriving confidence limits that can be determined from statistical analysis. By carrying out this type of analysis on the various data sources, an estimation of the variability of such data can be established.

Modelling uncertainty is concerned with the accuracy of the method chosen to calculate a risk in mathematical terms. An example of this type of uncertainty would be the prediction of crack growth in the wall of a pressure vessel. The model would postulate the way the growth rate is affected by factors such as the material properties and the stress. It should be remembered that such models are often based on idealised laboratory tests and that other factors encountered in real situations may affect their validity.

The specific targeting of inspection in areas of plant considered to be at greater risk of failure means that there will be other areas that are not examined as comprehensively or frequently. This may create more uncertainty and the possibility of an unexpected failure in these areas.

Sample (%) inspection is widely used both in initial construction and during service, but the inherent risk in doing so should always be taken into account. Where restrictions to inspection by NDT are anticipated, pressure vessel codes take this into account by adopting lower allowable stresses or by introducing 'weld factors', both of which are essentially safety margins.

There is also the phenomena known as 'limited predictability or unpredictability'. This describes cliff-edge situations where the outcomes are sensitive to small changes or combinations of the assumed conditions or initiating events. Just because events begin from a similar nominal state, it does not follow that the final occurrence will always be the same.

Where the RBI team is aware of the possibility of such situations, these should be investigated by means of sensitivity studies over the range of inputs. Whilst it may appear that such sequences of events are chaotic and unpredictable, the assessment team should try to envisage the incredible situations. In practice, the incredible happens surprisingly often.

9.6. A DYNAMIC PROCESS – THE NEED FOR RE-ASSESSMENT

Risk assessment is carried out on the basis of the data and information for the plant in question and the knowledge and experience of the RBI team at the time. It is important that up-to-date risk assessments are maintained.

When the whole basis of a risk assessment changes, then it is vital that a re-assessment is carried out. Although previous assessments may reflect good engineering judgement and experience, it is always necessary to review and re-validate the assumptions using the most recent information available.

Risk assessment is ‘state of knowledge’ specific and since many inputs change with time, the assessment can only reflect the situation at the time the data was collected. The risk ranking process is dynamic and will change with operating history and the results of inspection. Re-assessment of the risk should therefore be undertaken at relevant stages of the plant life cycle.

It is considered best practice to make a re-assessment of the risk before each thorough examination and to evaluate whether the basis of the previous risk assessment remains valid. The timing of the risk re-assessment should therefore coincide with at least each thorough examination.

Re-assessment should be carried out at other times during service if key data used in the risk assessment changes or as a result of events or changes in circumstances. It is therefore important that lines of communications between the plant operators and the RBI team are identified and remain open whilst the plant is operating. Changes and events that might justify a re-assessment could include:

- A serious process or operational upset.
- Failure of an item of equipment.
- Change in the operational regime.
- Change in the internal or external operating environment.
- Where time dependant operating conditions exist such as fatigue or creep.
- Change in industry practice.
- Change in plant management or ownership.
- Change in the level of operator training and knowledge.

Re-assessment is appropriate as new NDT techniques become available and offer Duty Holders the prospect of obtaining information not previously available. This should take into account the differences in capability between previous inspection techniques and the possible techniques to be used in the future. Care should be taken when changing the inspection technique to ensure continuity of information and plant knowledge.

9.7. SUMMARY OF MAIN POINTS

- (a) Risk based principles should be applied to the assessment of examination results and fitness-for-service, and the resulting course of action.

- (b) There are particular risks associated with repairs and modifications to plant and appropriate information must be given to the RBI team.
- (c) The composition of the team involved in the risk re-assessment process should mirror those involved in the original assessment.
- (d) Evidence of risk re-assessment after examination should be available.
- (e) Changes to the initial risk assessment following re-assessment should be documented.
- (f) Procedures should be in place to drive and control the re-assessment.
- (g) The plant database should be updated when there are changes in the equipment, process or state of knowledge that could affect the risk.
- (h) Remaining uncertainty should be allowed for in future inspection plans.
- (i) Sensitivity studies on initial data/assumptions should be carried out.
- (j) Lines of communication between the plant operators and the RBI assessment team should be clearly identified and remain open while the plant is operating.

9.8. REFERENCES FROM CHAPTER 9

9.1 British Standards: 'Guide on methods for assessing the acceptability of flaws in metallic structures', BS 7910:2000, ISBN 0 580 33081 8, 2000.

9.2 British Energy: 'R6: Assessment of the integrity of structures containing defects – Revision 3'. February 1997, available from British Energy, Barnwood, Gloucs.

9.3 American Petroleum Institute: 'Recommended practice for fitness for service', API 579, available from the American Petroleum Institute.

9.4 'The Pressure Systems Safety Regulations 2000', SI-2000-128. The Stationary Office.

10. EVIDENCE OF EFFECTIVE MANAGEMENT

10.1. MANAGEMENT OF THE PROCESS

Like other activities relating to Health and Safety, risk based inspection (RBI) requires effective management if it is to be implemented successfully. The HSE has published general guidance for successful Health and Safety management (10.1), and the principles of this document are applicable to the management of RBI. The issues addressed can be used by organisations for self audit and developing programmes for improvement.

Testing the performance of organisations, whether by internal or external audit, requires documentary evidence to be made available. The management of RBI is no exception, and evidence is required to cover all stages of the process. As the scope of RBI is wide, the amount of documentary evidence needed may be large.

Managing the inspection of complex high integrity installations should be a rigorous undertaking. Evidence is required to certify that each stage has been satisfactorily completed, for example, by means of a quality plan or equivalent documentation. For simple systems, or single items where the risks are clear, the written scheme of examination certified by the Competent Person is the key document.

RBI uses information from many different sources. Since inspection is part of the process of maintaining Health and Safety, the quality of this information must be demonstrably high. For example, documents and drawings should be validated within the organisation's quality assurance system.

The following sections are based on the HSE Guidance for Successful Health and Safety Management (10.1). They indicate the type of documentary evidence that might be required for an audit of inspection planning and implementation. Evidence that might be specific for inspection within a risk based framework is highlighted.

10.2. OBJECTIVES

In many organisations, the objectives of plant inspection are not extensively documented. Information, if it exists, might be found in:

- Corporate policies.
- Contract documents with third party inspection companies.
- Conditions imposed as part of insurance policies.

The objectives of inspection could be expressed in terms of measurable Health and Safety and business performance targets, for example:

- Number of equipment failures per year with no risk to personnel.
- Number of equipment failures per year where personnel were at risk or injured.
- Amount of lost production resulting from equipment failures per year.

More advanced industries and companies are now setting themselves targets of this kind. Asking a company why plant is being inspected may be revealing about their

attitudes to efficiency and Health and Safety. 'In order to meet the regulations' is an answer that, on its own, suggests that insufficient consideration has been given.

10.3. ALLOCATION OF RESPONSIBILITIES, ACCOUNTABILITY AND RESOURCES

Usually, the planning and implementing of RBI requires a team of individuals and sometimes several organisations to act in a co-ordinated way. Their roles and responsibilities within the process need to be clearly allocated. Documentary evidence for clear allocation of responsibilities may include:

- Reference within individual job descriptions.
- Inspection manual/work instructions.
- Company policy documents/internal memos.
- Written statements of business/department/individual objectives and targets.
- Contract agreements with third party inspection services.
- Conditions contained within insurance policies.
- Organisation charts of the structure of the RBI team.

Defining the authority and responsibility of the team leader is of particular importance. The holders of the different roles of the Competent Person must be made clear together with any requirements to consult the Corporate Body. Where experts are used to make judgements in the risk analysis, the documentation should state their areas of expertise.

Evidence of accountability of the participating individuals and organisations is necessary as a check on their performance. Documentary evidence of how people and organisations are held accountable would include the existence of:

- Regular performance reviews and staff appraisals.
- Performance reports to senior management.
- Contract reviews with Competent Person organisations.
- Peer assessments of independent experts.
- Wider reviews of the system operating the process of RBI.

RBI requires the allocation of sufficient resources to the team in terms of staffing and finance. Information should be available in order for the level of resourcing to be assessed. Relevant documents could include:

- Records of meetings
- Staff time sheets
- Departmental staffing plans
- Budgetary plans or forecasts
- Contract documents
- Cost accounts or business reports

10.4. CO-OPERATION

RBI requires a high degree of co-operation between different departments of the Duty Holder's organisation, the Competent Person, and independent experts.

Evidence of good co-operation can usually be obtained from the number of meetings, minutes of meetings and correspondence. Failures in co-operation may be harder to detect and are less likely to be documented.

One problem is the amount of time that key staff are able to allocate, either from pressure of their own departments, or restriction in the RBI budget. Non attendance at meetings, or failure to deliver reports, could be an indication of this. A short time-scale for the planning exercise is another reason for non co-operation: indicators could be the degree of notice given in relation to the scheduled start of the inspection or memos requesting information in a short period.

RBI may involve change to established inspection regimes and this can give rise to discontent from operators and inspection departments. Problems can arise during the specification of reliable inspection where previous practice may be questioned or need to be qualified. Issues such as these could be revealed in the minutes of safety committee or production planning meetings.

10.5. COMMUNICATIONS

Communications and the availability of information as essential elements of the RBI process. The relevant information must be made available to the RBI team and evidence of this could be a document register and distribution lists. Historical performance data, operating experience and previous inspection records, all need to be adequately documented.

Minutes of meetings should be readily available. This is particularly important when risks are assessed and qualitative judgements made. Decisions need to be justified, particularly on issues such as exclusion from inspection/prioritisation/sampling etc.

The quality and authority of communications is at least as important as the quantity. Good communications may be judged by reference to:

- The number and detail of formal memoranda.
- The number and frequency of minuted meetings.
- Inspection procedures/instruction manuals.
- Written schemes of examination.
- Job requests and work specifications.
- Progress chasing/action lists.

10.6. COMPETENCE OF RBI TEAM

RBI planning teams (including the Competent Person and independent experts) and staff implementing inspection of safety critical equipment must be competent as demonstrated through having adequate:

- Training
- Qualifications
- Experience

Evidence of competence covering these areas may be available in curriculum vitae and other documents which could include:

- Job selection and recruitment criteria
- Qualification certificates
- Membership of professional bodies
- Inspection accreditation certificates
- Certificate of completion of training
- Training appraisals and competency assessments

10.7. RISK ANALYSIS AND INSPECTION PLANNING

At the end of the risk analysis phase, the key documents that can be reviewed should include:

- List of equipment within the plant boundary considered.
- Accident scenario descriptions – HAZOPs, FMEA, reports etc.
- Evidence of potential deterioration mechanisms from previous inspection reports/operating data/industry generic data/check lists/expert elicitation reports.
- Consequence calculations and assessments.
- Results of the risk analysis including any categorisation and ranking.

At the end of the inspection planning phase, the key documents are:

- Written schemes of examinations and whole plant inspection programmes.
- Lists of equipment included and excluded from examination.
- Certification of the written scheme by the Competent Person.
- Inspection standards, manufacturers handbooks/manuals, operating instructions.
- Inspection procedures and requirements for qualification.
- Instructions for preparing plant for inspection and safety cover.
- Requirements for monitoring and other measures for safety management.

Duty Holders and the Competent Person should be able to state the relevant factors that they have considered when developing written schemes of examination and proposed intervals between examinations. An audit should examine their degree of knowledge or uncertainty about each factor. They should be able to draw attention to any special factors that might be relevant.

A more holistic view of the role of inspection in maintaining plant safety might be obtained from references to inspection in safety reports and safety cases.

10.8. IMPLEMENTATION

Checks on the proper implementation of the inspection are the responsibility of both the Duty Holder and Competent Person. The key documents are:

- Inspection qualification reports or certificates (where required).
- Authenticated reports of the examinations carried out.
- Fitness certificates (for valves, safety devices etc.).

- Fitness-for-service assessments of reportable flaws.
- Reports specifying where repairs, or modifications, or changes to the operating conditions are required before further operation (in case of imminent danger) or within a specified time limit.
- Reports covering the re-examination of modified or repaired equipment.
- Minutes of meetings reviewing the results of inspection, making modifications to the risk analysis or written scheme, and specifying the maximum period until the next examination.

Within a risk-based framework, the examination reports should highlight factors that could have reduced the expected reliability or coverage of the examination. Examples could be poor surface finish, access problems, or difficulties due to insulation, coatings etc. Where inspection qualification has been a requirement, the qualification should be updated if feedback from site experience shows evidence that these factors deviated from what was anticipated.

Fitness-for-service assessments are now becoming common engineering practice, since the risk associated with repairs, or modifications, could out-weigh the risks of leaving a defect in place. Assessments should be made to recognised methodologies (e.g. BS 7910 (10.2) or API 579) properly recorded, and approved. Inspection sizing data upon which such assessments are made should be obtained using approved procedures with due allowance for potential errors.

Feedback of the knowledge gained about the condition of equipment from inspection is an essential part of the process since it can change the prior assessment of the risks from future operation. Implementation of RBI is not finished until the risk analysis and the written schemes are updated. This might be an opportunity to extend operating intervals when conditions are favourable. When deterioration has been detected, there may be a need for more frequent inspection.

Duty Holders should keep records of current and previous examinations of pressure systems as specified in the Pressure System Safety Regulations 2000 (PSSR) (10.4).

10.9. MEASURING PERFORMANCE

The operation of planned programmes of inspection should be monitored to ensure that they are being carried out. This applies particularly to the continued use of equipment beyond the due inspection date, and when the inspection is not carried out according to the written schemes of examination. Duty Holders should have within their quality assurance system:

- Procedures for independent monitoring of performance of planned inspection.
- Procedures for dealing with overdue inspection and non-conformance to written schemes of examination.

Documentary evidence indicating the performance is likely to be found in:

- Internal correspondence highlighting when inspection/repairs are overdue.
- Reports of performance monitoring within the quality system.
- Comparison of written schemes with inspections report records.

- Forward planning indicators for operations staff.
- Reports on overdue inspection/repairs.
- Lack of information showing feedback into future inspection planning.
- Reports indicating failure to inspect or to properly inspect or to inspect on time.

The PSSR allow the date of an examination to be postponed once by agreement in writing between the Duty Holder and the Competent Person ‘providing such postponement does not give rise to danger’. The enforcing authority must be informed of such a decision before the original inspection date, and Duty Holders should be expected to have adequate documentary evidence of the basis for the decision to postpone.

10.10. REVIEWING PERFORMANCE OF THE WHOLE PROCESS

This is a higher level activity undertaken by management to ensure that the whole process of RBI is operating effectively and to identify areas where performance of the process could be improved. Such reviews are likely to be linked to wider assessments such as:

- Operating performance reviews.
- Outage planning.
- Plans for the introduction of new/replacement equipment.
- Plant/business risk assessments, HAZOPs/FMEA.
- External quality audit reports.
- Investigation of equipment failures and incidents.

Documentary evidence for performance review is likely to be found in internal company procedures and reports to senior management. Aspects that could be subject to change from performance review might include the risk targets or definitions, composition of RBI teams, re-appointment of Competent Persons, and systems of documentation and record keeping. Evidence of approved changes in the policy or process of inspection planning, and implementation, should be available.

10.11. AUDITING THE PROCESS

The whole process of inspection planning and implementation is expected to be subject to periodic auditing by an independent body internal or external to the company. This is normally carried out as part of the regular check on the quality system or Health and Safety management. The audit should establish that the process exists and is properly designed, is being operated at all stages, and is effective at meeting its objectives. Documentary evidence of auditing is likely to come from audit reports and any statements of non-conformance.

With RBI, it is important that auditors are able to investigate the more technical aspects and assess the processes by which judgements about risk are being made. This may require specialised knowledge. A set of questions to assist auditors is given in Appendix B. Audits of the process must cover the roles and responsibilities of non-company staff such as Competent Persons and independent experts.

10.12. SUMMARY OF MAIN POINTS

- (a) Duty Holders should periodically self-audit and review the effectiveness of their arrangements for managing RBI.
- (b) Appropriate documentary evidence and quality of information should be available to enable such an audit to take place.
- (c) The scope of the audit should follow the principles given in the HSE Guidance for Successful Health and Safety Management (10.1).
- (d) Within RBI, the data and processes used for making judgements and assessments of risk should be given particular scrutiny. Information availability, flow, and transparency of decision making are especially important.
- (e) As a result of the audit and review, Duty Holders should develop programmes to improve their management arrangements where this is necessary.

10.13. REFERENCES FROM CHAPTER 10

10.1 Health and Safety Executive. 'Successful Health and Safety Management'. HS(G) 65. ISBN 0-7176-0425-X. Published by HSE Books.

10.2 British Standards: 'Guide on methods for assessing the acceptability of flaws in metallic structures', BS 7910:2000, ISBN 0 580 33081 8, 2000.

10.3 American Petroleum Institute: 'Recommended practice for fitness for service', API 579, available from the American Petroleum Institute.

10.4 'The Pressure Systems Safety Regulations 2000', SI-2000-128. The Stationary Office.

APPENDIX A

CASE STUDY OF RISK BASED INSPECTION PRACTICE

A1. INTRODUCTION

This Authoritative Technical Review systematically assesses the risk of items of equipment within Plant A with the intention of extending the thorough inspection periodicity from 26 months to 48 months, in accordance with the Pressure Systems Safety Regulations 2000.

This report, produced by both the User/Operator of the system and the Competent Person responsible for carrying out the routine inspection of the system, gives details of the review carried out of, what is considered to be, all the relevant factors related to the safety of the system. This includes, but is not limited to, a review of (i) the design documentation (ii) the inspection history and (iii) the operational and maintenance history.

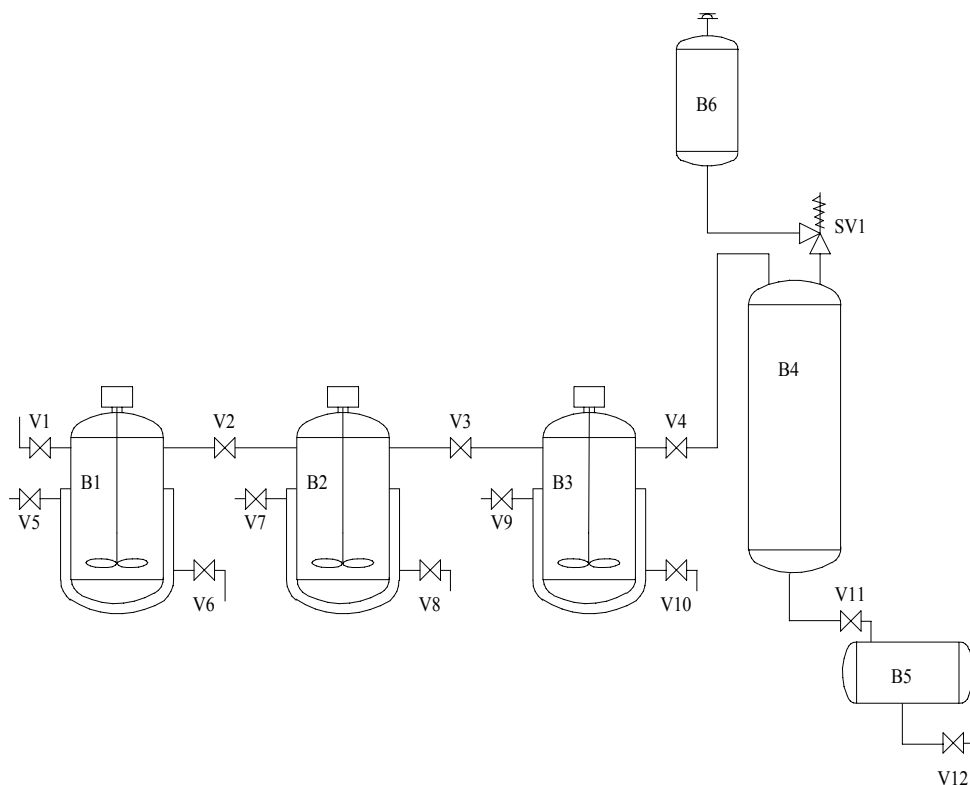
The review describes the current condition of the plant and where appropriate identifies any additional inspection and maintenance requirements that are considered necessary to enable the current statutory inspection interval to be increased.

Copies of all material referred to in this review, where possible, have been collated and are to be found in the Appendix at the back of this report.

The contents of this report should be included within, or as an appendix to, the Written Scheme of Examination held by the User.

A2. SUMMARY OF SYSTEM

Schematic of Pressure System:



Pressure system reference : 0020 – I – 10 : Process A

Relevant fluid : Nitrogen

Extent of system : From product inlet valve V1 on jacketed process vessel B1 terminating at the outlet valve V12 on reflux drum B5, including all pipework and safety valve catchpot.

List of items within system :

User Ref	Description of Item
B1	Jacketed Process Vessel
B2	Jacketed Process Vessel
B3	Jacketed Process Vessel
B4	Catalyst Column
B5	Reflux Drum
B6	Catchpot
B7	Pipework

Interrelationships with other systems:

The product is fed from the storage facility into vessel B1 through valve V1. Various additives are incorporated throughout the process, which is kept under a blanket of Nitrogen at a pressure of 3.0 barg, and the product is cleaned within the catalyst column B4 and stored in vessel B5 ready for despatch via valve V12. The nitrogen is

fed via pressure system 0019 – S – 10. The jackets are heated with hot water at a temperature not exceeding 85°C and at atmospheric pressure.

Other items within system:

The product is pumped through the system, pumps P1 and P2 are covered by the routine maintenance system and are not included in this technical review. The valves V1 to V12 inclusive are included as part of the pipework B7. All other items within the system are included.

Maintenance of the system:

The pumps, associated valves and agitators in vessels B1, B2 and B3 are subjected to routine maintenance which includes full strip down and overhaul at every planned outage i.e. 26 months. The maintenance reports for the last 4 outages have been reviewed, with the results being consistent and acceptable in view of the proposed overhaul being conducted at a periodicity of 48 months.

Information:

Full documentation was available for review on all items apart from the reflux drum B5, where very little information was found with respect to the original design and construction and no detailed examination has been carried out in service.

Previous inspections:

The system has been inspected by a Competent Person since the implementation of the Pressure Systems and Transportable Gas Containers Regulation 1989. All examination reports have been reviewed.

A3. TEAM DETAILS

Team Leader : A N Other 1 CEng MIMechE Consultant Engineer- Competent Person
A N Other 2 CEng MIPlantE Plant Engineer – User
A N Other 3 CEng MIProdE Production Engineer – User
A N Other 4 CEng MIM Metallurgist – Competent Person
A N Other 5 PCN Level 3 NDT Specialist – Competent Person
A N Other 6 NEBOSH Diploma Health and Safety Adviser – User

Terms of reference:

The risk assessment is to be carried out using the semi-quantitative approach using a 5 x 5 matrix to establish the level of risk. Meetings to be held on a fortnightly basis with the minutes documented for future reference. All communications to be copied to the team leader for his retention in the main assessment file.

A4. ASSESSMENT OF RISK

The assessment of risk is based on the following parameters, with each item within the system being reviewed and assessed against the known failure modes and damage mechanisms :

Failure Modes:

Protective Device – The whole system is protected by 1 off spring loaded safety valve. At every outage this valve has been tested in as-removed condition, stripped down, overhauled and retested prior to being re-installed. All data associated with this overhaul is available for review.

Corrosion – Internal corrosion has been identified as a potential damage mechanism throughout the system. The rates of corrosion have been established from the previous examination results. The external surfaces are unlagged and coated to prevent external corrosion.

Creep – The operating temperature of this process is maintained at approximately 80°C and therefore creep is not considered as a potential failure mode.

Fatigue – The three jacketed process vessels have agitators fitted which impart a localised cyclic loading at the nozzle/shell connection. The main process is considered to be in steady state operation and therefore fatigue is not considered as a potential failure mode.

Stress Corrosion Cracking and other material/environment combinations – These are not considered as a potential failure mode in the jacketed process vessels. Experience indicates, however, that the potential for stress corrosion cracking may occur in the welds at the high stressed areas of the catalyst column.

Brittle Fracture – The operating temperature does not drop down to temperatures where brittle fracture would be a potential failure mode. The plant is indoors and undercover.

Buckling – The operating parameters prevent a vacuum condition occurring, buckling is therefore not considered.

Operator Error – All operating conditions (including start-up, shut down and normal operation) are automatically controlled and monitored by a computerised system. Operator error is therefore highly unlikely.

Probability of Failure

Internal Corrosion:

Rating	Description
Highly probable	Allowable loss is already used up
Probable	Remaining life 3 - 5 years
Possible	Remaining life 5 – 7 years
Unlikely	Remaining life 7 – 10 years
Very unlikely	Remaining life > 10 years

Fatigue:

Rating	Description
Highly probable	Operating life > 60% Design life
Probable	Operating life < 60% Design life
Possible	Operating life < 40% Design life
Unlikely	Operating life < 20% Design life
Very unlikely	Not considered significant

Stress Corrosion Cracking:

Rating	Description
Highly probable	Experience of wide spread cracking in similar vessels
Probable	Experience of very localised cracking in similar vessels
Possible	Very little experience of cracking in similar vessels
Unlikely	No experience of cracking in similar vessels
Very unlikely	Not considered significant

Consequence of Failure

Impact of production:

Rating	Description
4	Sudden failure possible – Prolonged repair
3	Sudden failure possible – Short repair
2	Predictable failure – Planned repair
1	Standby plant – Little or no impact

Location - Personnel:

Rating	Description
3	Heavily populated
2	Routinely accessible
1	Inaccessible without clearance

Location - Equipment:

Rating	Description
3	Dense installation
2	General installation
1	Remote installation

Fluid Characteristics:

Rating	Description
3	Hazardous
2	Hydrocarbons – neither inert or hazardous
1	Inert/less than 100°C

Fluid Hazard - Contents:

Rating	Description
3	Notifiable substance > prescribed quantity
2	Notifiable substance < prescribed quantity
1	No notifiable substance

Fluid Hazard - Pressure:

Rating	Description
3	> 30 Bar
2	> 7 Bar < 30 Bar
1	< 7 Bar

Consequence Rating:

Rating	Description
Very high	16 – 19
High	13 – 15
Moderate	10 – 12
Low	8 – 10
Very low	6 – 8

Overall Risk Rating :

		Probability of failure				
Consequence of failure		Highly probable	Probable	Possible	Unlikely	Very unlikely
	Very high	Very high	Very high	High	Moderate	Low
	High	Very high	High	Moderate	Low	Low
	Moderate	High	Moderate	Moderate	Low	Very low
	Low	Moderate	Low	Low	Low	Very low
	Very low	Low	Low	Very Low	Very Low	Very low

(a) Vessels B1, B2 and B3 : Jacketed Process Vessel

Probability –

Internal Corrosion/Erosion: At the current corrosion rate it is calculated that the remaining life is in excess of 10 years.∴ Very Unlikely

Fatigue: The loading by the agitator is very low and well below 20% design life ∴ Unlikely

Stress Corrosion Cracking : This is not considered significant ∴ Very Unlikely

Probability Rating: Unlikely

Consequence –

Impact of production : The anticipated failure modes are unlikely to occur in a sudden manner and therefore any potential repair can be planned ∴ 2

Location - Personnel : The location is only accessible with clearance from control room ∴ 2

Location - Equipment : The location is relatively dense and any failure could have an impact on surrounding equipment ∴ 3

Fluid Characteristics : The process fluid is a non-hazardous hydrocarbon ∴ 2

Fluid Hazard - Contents : The process fluid is a notifiable substance, however the quantity is below that prescribed ∴ 2

Fluid Hazard - Pressure : The process fluid is at a pressure not exceeding 3 barg ∴ 1

Consequence Rating : 12 Moderate

Consequence of failure		Probability of failure				
		Highly probable	Probable	Possible	Unlikely	Very unlikely
	Very high					
	High					
	Moderate				Low	
	Low					
	Very low					

Overall Risk Rating = Low

Inspection Plan

Failure Mode	Scope of Examination
General Condition	Internal and external examination of all accessible parts of the vessel, support structures and fittings for corrosion, deformation, cracking, leakage and other weld or plate defects.
Internal Corrosion/Erosion	Ultrasonic thickness measurement of inner vessel on a 500mm grid pattern. Any area that indicates thinning should be subjected to scanning to establish the extent of the thinning.
Fatigue	Surface crack detection of nozzle/shell connection weld internally and externally using magnetic particle inspection or eddy current technique.

Reassessment of Probability (Based on adoption of inspection plan) –

Internal Corrosion/Erosion : At the current corrosion rate it is calculated that the remaining life is in excess of 10 years ∴ Very Unlikely

Fatigue : The local loading imposed by the agitator is very low and is well below 20% design life. In-service examination developed to target this area ∴ Very Unlikely (subject to satisfactory examination results).

Stress Corrosion Cracking : This is not considered significant ∴ Very Unlikely

Probability Rating : Very Unlikely

		Probability of failure				
Consequence of failure		Highly probable	Probable	Possible	Unlikely	Very unlikely
	Very high					
	High					
	Moderate					Very low
	Low					
	Very low					

Overall Risk Rating = Very Low

Examination Periodicity:

The frequency of the thorough examination of this item of plant detailed in this review can be extended from 26 months to 48 months provided that:

- 1) The assessed as part of this review remain valid. The Competent Person responsible for this review, should be made aware of any changes with respect to the data used to enable a re-assessment to be carried out.
- 2) The examination requirements detailed above are adhered to.
- 3) The results of any future examination are assessed in conjunction with this review to ensure that all details and assumptions remain valid.

(b) Vessel B4: Catalyst Column

Probability –

Internal Corrosion : Previous examination reports have indicated that internal corrosion is occurring, however the vessel has not had an internal examination since installation (8 years) and any thickness measurement has been carried out from the external surface in a random pattern. Due to the non-intrusive examination techniques being adopted an allowance has been made in the probability rating. ∴ Possible

Fatigue : Not considered significant ∴ Very Unlikely

Stress Corrosion Cracking : Although not found during routine examinations, the Competent Person has experience of very localised cracking in similar vessels ∴ Probable

Probability Rating : Probable

Consequence –

Impact of production : The anticipated failure modes are likely to occur in a sudden manner which may result in prolonged repair ∴ 4

Location - Personnel : The location is only accessible with clearance from control room ∴ 2

Location - Equipment : The location is relatively dense and any failure could have an impact on surrounding equipment ∴ 3

Fluid Characteristics : The process fluid is a non-hazardous hydrocarbon ∴ 2

Fluid Hazard - Contents : The process fluid is a notifiable substance, however the quantity is below that prescribed ∴ 2

Fluid Hazard - Pressure : The process fluid is at a pressure not exceeding 3 barg ∴ 1

Consequence Rating : 14 High

Consequence of failure		Probability of failure				
		Highly probable	Probable	Possible	Unlikely	Very unlikely
	Very high					
	High		High			
	Moderate					
	Low					
	Very low					

Overall Risk Rating = High

Inspection Plan

Failure Mode	Scope of Examination
General Condition	External examination of all accessible parts of the vessel, support structures and fittings for corrosion, deformation, cracking, leakage and other weld or plate defects.
Internal Corrosion/Erosion	Ultrasonic thickness mapping of vessel shell and heads, from the external surface, using an automated ultrasonic pulse-echo technique. Any area that indicates thinning should be subjected to further analysis.
Failure Mode	Scope of Examination
Stress Corrosion Cracking	Ultrasonic flaw detection for internal surface breaking defects from the external surface externally. All high stressed areas to be included in this examination i.e. a) All main weld 'T' junctions b) Nozzle / shell junctions
Protective Device	The safety valve should be removed, tested in the 'as-removed' condition, overhauled and replaced at every thorough examination.

Reassessment of Probability (Based on adoption of inspection plan) –

Internal Corrosion/Erosion : With a more rigorous, defined procedure for mapping the whole of the vessel, a benchmark for future examinations can be developed. All results can be compared with original 'as-built' thicknesses etc. to establish corrosion rates ∴ Very Unlikely (subject to satisfactory examination results).

Stress Corrosion Cracking : Using an examination technique, specifically to identify this potential failure mode then greater confidence in vessel integrity can be achieved.
∴ Unlikely (subject to satisfactory examination results).

Probability Rating : Unlikely

Reassessment of Consequence (Based on adoption of inspection plan) –

Impact of production : The anticipated failure modes are not likely to occur in a sudden manner as corrosion rates will be established ∴ 2

Consequence Rating : 12 Moderate

		Probability of failure				
Consequence of failure		Highly probable	Probable	Possible	Unlikely	Very unlikely
	Very high					
	High					
	Moderate				Low	
	Low					
	Very low					

Overall Risk Rating = Low

Examination Periodicity:

The frequency of the thorough examination of this item of plant detailed in this review can be extended from 26 months to 48 months provided that:

- 1) The details assessed as part of this review remain valid. The Competent Person responsible for this review, should be made aware of any changes with respect to the data used to enable a re-assessment to be carried out.
- 2) The examination requirements detailed above are adhered to.
- 3) The results of any future examination are assessed in conjunction with this review to ensure that all details and assumptions remain valid.

(c) Vessel B5: Reflux drum

Probability –

Internal Corrosion : There are no previous examination reports so it must be assumed that the allowable loss has already been used up ∴ Highly Probable

Fatigue : Not considered significant ∴ Very Unlikely

Stress Corrosion Cracking : Not considered significant ∴ Very Unlikely

Probability Rating: Highly Probable

Consequence –

Impact of production : As there is no known benchmarking due to lack of manufacturing information it cannot be assumed that the anticipated failure modes are unlikely to occur in a sudden manner ∴ 4

Location - Personnel : The location is only accessible with clearance from control room ∴ 2

Location - Equipment : The location is relatively dense and any failure could have an impact on surrounding equipment ∴ 3

Fluid Characteristics : The process fluid is a non-hazardous hydrocarbon ∴ 2

Fluid Hazard - Contents : The process fluid is a notifiable substance, however the quantity is below that prescribed ∴ 2

Fluid Hazard - Pressure : The process fluid is at a pressure not exceeding 3 barg ∴ 1

Consequence Rating : 14 High

Consequence of failure		Probability of failure				
		Highly probable	Probable	Possible	Unlikely	Very unlikely
	Very high					
	High	Very high				
	Moderate					
	Low					
	Very low					

Overall Risk Rating = Very High

Inspection Plan

Failure Mode	Scope of Examination
General Condition	Internal and external examination of all accessible parts of the vessel, support structures and fittings for corrosion, deformation, cracking, leakage and other weld or plate defects.
Internal Corrosion/Erosion	Ultrasonic thickness mapping of vessel shell and heads, from the external surface, using an automated ultrasonic pulse-echo technique. Any area that indicates thinning should be subjected to further analysis. Supporting calculations are to be carried out to establish the minimum material thickness required for the safe operating limits of this item.

Reassessment of Probability (Based on adoption of inspection plan) –

Internal Corrosion/Erosion : The corrosion rate is not known. The probability of failure under this mode remains the same. ∴ Highly Probable

Fatigue : This is not considered significant ∴ Very Unlikely

Stress Corrosion Cracking : This is not considered significant ∴ Very Unlikely

Probability Rating : Highly Probable

Reassessment of Consequence (Based on adoption of inspection plan) –

Impact of production : Provided that the actual material thickness is greater than the minimum calculated thickness it can be said that any failure would be predictable
∴ 2

Consequence Rating : 12 Moderate

Consequence of failure		Probability of Failure				
		Highly probable	Probable	Possible	Unlikely	Very unlikely
	Very high					
	High					
	Moderate	High				
	Low					
	Very low					

Overall Risk Rating = High

Examination Periodicity:

The frequency of the thorough examination of this item of plant detailed in this review should remain at 26 months until the corrosion rate can be established i.e. following the subsequent thorough examination after the adoption of the above inspection plan.

(d) Vessel B6 : Catchpot

Probability –

Internal Corrosion : At the current corrosion rate it is calculated that the remaining life is in excess of 10 years ∴ Very Unlikely

Fatigue : Not considered significant ∴ Very Unlikely

Stress Corrosion Cracking : No experience of cracking in similar vessels ∴ Unlikely

Probability Rating : Unlikely

Consequence –

Impact of production : The anticipated failure modes are unlikely to occur in a sudden manner and therefore any potential repair can be planned ∴ 2

Location - Personnel : The vessel location is only accessible with clearance from control room ∴ 2

Location - Equipment : The vessel location is relatively remote and any failure would not have an impact on surrounding equipment ∴ 1

Fluid Characteristics : The process fluid is a non-hazardous hydrocarbon ∴ 2

Fluid Hazard - Contents : The process fluid is a notifiable substance, however the quantity is below that prescribed ∴ 2

Fluid Hazard - Pressure : The process fluid is at a pressure not exceeding 3 barg ∴ 1

Consequence Rating: 10 Low

Consequence of failure		Probability of Failure				
		Highly probable	Probable	Possible	Unlikely	Very unlikely
	Very high					
	High					
	Moderate					
	Low				Low	
	Very low					

Overall Risk Rating = Low

Inspection Plan

Failure Mode	Scope of Examination
General Condition	Internal and external examination of all accessible parts of the vessel, support structures and fittings for corrosion, deformation, cracking, leakage and other weld or plate defects.
Internal Corrosion/Erosion	Ultrasonic thickness measurement of inner vessel on a 500mm grid pattern. Any area that indicates thinning should be subjected to scanning to establish the extent of the thinning.
Protective Devices	The bursting disc should be replaced at every vessel thorough examination.

Examination Periodicity:

As the corrosion rates that have been established for this item of plant are very low (< 0.10 mm / year) it is considered that the frequency of the thorough examination can be extended from 26 months to 48 months provided that :

- 1) The details assessed as part of this review remain valid. The Competent Person responsible for this review, should be made aware of any changes with respect to the data used to enable a re-assessment to be carried out.
- 2) The examination requirements detailed above are adhered to.
- 3) The results of any future examination are assessed in conjunction with this review to ensure that all details and assumptions remain valid.

A5. CONCLUSIONS

The risk rating process is dynamic and any changes in the data used should be re-assessed or refined on an ongoing basis. It is considered best practice for the re-assessment to take place prior to each thorough examination, when all the data used and assumptions made can be validated.

This review should therefore be re-assessed immediately following the forthcoming examination and again just prior to the next scheduled examination.

A record, of these re-assessments, should be maintained which details the outcomes and amendments made.

APPENDIX B

AUDIT TOOL FOR RISK BASED INSPECTION

AUDIT TOOL FOR RISK BASED INSPECTION

The following series of questions is intended to assist Duty Holders evaluate the processes they are using for integrity management and inspection planning of pressure systems and other systems containing hazardous materials. It follows the stages in the following process flow diagram. More information and explanation of the audit tool is given in the main report.

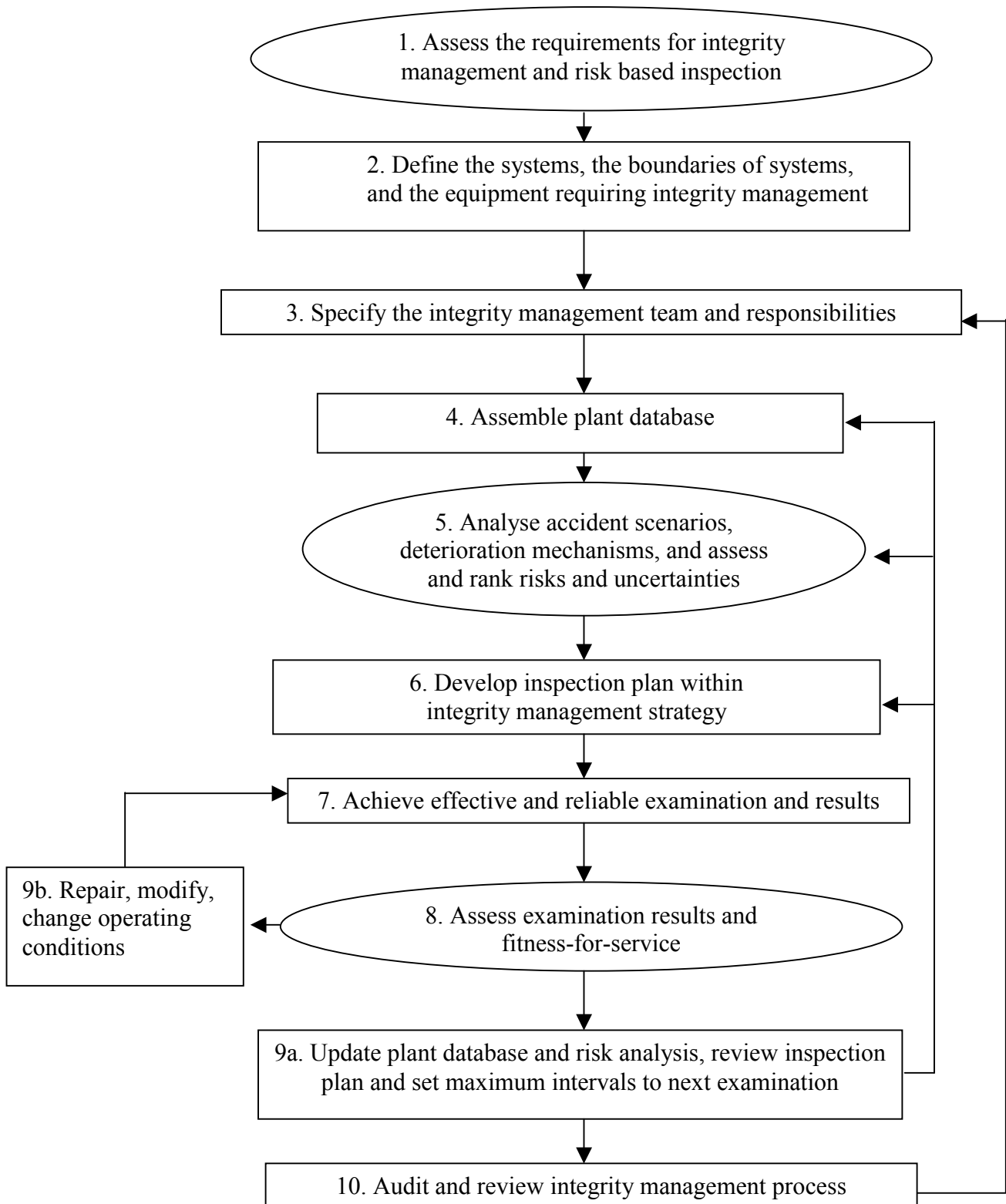


Fig.B1 – Process diagram for plant integrity management by risk based inspection

B1. ASSESSING THE REQUIREMENTS FOR RISK BASED INSPECTION

B1.1. WHAT REFERENCE HAS BEEN MADE TO PUBLISHED INFORMATION?

The requirements for integrity management and risk based inspection of potentially hazardous plant can be determined by reference to Health and Safety regulations, industry standards and guidelines, and other literature. These can provide valuable information on hazards and control measures as well as covering compliance with Duty Holder's statutory obligations.

B1.2. WHAT ARE THE REASONS/DRIVERS FOR THE RISK BASED APPROACH?

The main objective of risk based integrity management is to understand and manage the risks of failure of potentially hazardous plant to a level that is acceptable to the organisation and the society within which it operates. Risk based inspection should aim to target finite inspection resources to areas where potential deterioration can lead to high risks. All the objectives of the risk based approach need to be clearly stated at the outset of the process.

Duty Holders may wish to consider a wide range of consequences of failure, but as a minimum these should include the Health and Safety of employees and the public, effects on the environment, and implications for their business. It is important that the risks associated with each of these consequences are considered separately and that measures are taken to manage the risks in each case. Duty Holders should ensure that inspection resources are adequate to manage all the risks, and that limited resources do not compromise Health and Safety or environmental risks.

B1.3. IS THE AVAILABILITY AND ACCURACY OF INFORMATION SUFFICIENT?

The assessment of risk depends on the availability and accuracy of the information relating to the systems and equipment to being assessed. Good information may enable a low risk to be justified, but does not in itself guarantee that the risks are low. Where information is lacking, unavailable, or uncertain, the risk is increased since it cannot be shown that unfavourable circumstances are absent.

The type of information required to assess the risk will vary depending on the type of plant, but should be identified at this early stage. The essential data needed to make a risk assessment should be available within the plant database. If it is obvious that the essential data does not exist, action to obtain this information is required or prescriptive inspection procedures should be applied.

B1.4. DOES THE APPROACH REFLECT THE COMPLEXITY OF THE PLANT?

The rigor of the RBI approach should reflect the complexity of the processes and the installation, as well as the severity of potential hazards and consequences of failure. Where causes and consequences of failure are easily identified as being limited, such as with an isolated boiler, a less rigorous approach may be appropriate. Multiple interacting systems require more detailed analysis of failure modes and effects, while systems whose failure would lead to a major catastrophe may require a full quantitative risk analysis.

B1.5. HOW DO INTEGRITY MANAGEMENT AND INSPECTION LINK TO PLANT OPERATIONS?

In practice, the integrity management process and inspection are required to integrate with plant operations. Often pressure systems and systems containing hazardous materials have to be depressurised or emptied for inspection, and plant and equipment may also be shut down for reasons of production, process efficiency and general maintenance. There should be no evidence, however, of plant operations compromising the integrity management process or delaying an inspection beyond that which has been justified by a risk assessment.

B1.6. HOW IS THE DOCUMENTATION MANAGED AND CONTROLLED?

Integrity management and inspection planning require documentation at all the key stages to enable a record, audit and review of the decision making processes. The quality of the information used needs to be verifiable. Duty Holders therefore need to consider at the outset how the traceability and quality of documentation are controlled.

B2. DEFINING THE SYSTEMS AND EQUIPMENT REQUIRING INTEGRITY MANAGEMENT

B2.1. ARE THE SYSTEMS REQUIRING INTEGRITY MANAGEMENT CLEARLY DEFINED?

UK Health and Safety regulations require Duty Holders to manage the integrity of pressure systems and other systems containing hazardous materials. In the first instance the hazard results from the release of stored energy, including the scolding effects of steam. In the latter instance, the hazard results from the dangerous properties of the fluid released, e.g. toxic, flammable, radioactive.

Each system should be clearly defined in terms of its constituent equipment: pressure vessels, pipework (including associated pumps, valves etc), pipelines and protective devices. This is a requirement of the Pressure Systems Safety Regulations 2000. The development of an inventory of systems and equipment comprising each system initiates the integrity management process.

B2.2. HAVE THE BOUNDARIES OF EVERY SYSTEM BEEN CLEARLY DEFINED?

Benefits can be achieved by breaking down large systems into smaller more manageable subsystems, usually having different failure modes and effects. This is particularly appropriate where there are different process conditions, process fluids, materials of construction, or where the consequences of failure could be changed such as by the walls of a building. The boundaries of each system need to be clearly defined on the basis of specific equipment, welds or connections.

B2.3. ARE ALL EQUIPMENT AND FACTORS RELEVANT TO THE RISK INCLUDED?

In order to develop a risk based integrity management and inspection regime for a system, all other equipment and factors that could impact on the risk of failure (likelihood and consequences) of the system need to be identified. These could include, for example, interacting systems, hangers and supports, operating and management regimes, control devices and power supplies, other plant or personnel that could be affected by failure, location, climate, and environment. This consideration of other equipment and factors needs to be wide-ranging.

Where the functioning of other equipment is associated with the risk of failure of pressure systems and containers of hazardous materials, then this equipment should also be included within the inventory of items for integrity management. These secondary items may be crucial to the safety of the primary systems and therefore require integrity management and inspection in their own right. These items, which may not normally be subject to statutory inspection, may include static storage tanks, pumping and cooling systems, civil structures, electrical and monitoring equipment, barriers and other protective equipment.

B3. SPECIFYING THE RBI MANAGEMENT TEAM AND RESPONSIBILITIES

B3.1. WHO IS MANAGING THE INTEGRITY MANAGEMENT PROCESS?

The person responsible on behalf of the Duty Holder for integrity management of the systems should normally lead a team for ensuring that an appropriate inspection plan is developed that adequately addresses the risks to Health and Safety.

B3.2. WHO ARE THE MEMBERS OF THE TEAM?

Integrity management and RBI is best undertaken by a team. For all but the simplest situations, the risk assessment and inspection planning processes require a range of technical inputs and perspectives from different disciplines and people.

B3.3. DOES THE TEAM HAVE KNOWLEDGE AND EXPERIENCE IN THE KEY AREAS?

The number of individuals and composition of the team depend on the complexity of the installation. All teams should have adequate knowledge and experience in the key areas. These areas include risk assessment, process hazards and plant safety, mechanical engineering including material science and plant design, plant operation and maintenance, the plant inspection history, and non-destructive testing.

B3.4. DO THE TEAM MEMBERS HAVE ADEQUATE QUALIFICATIONS AND COMPETENCE?

Where significant Health and Safety risks could arise from equipment failure, the qualifications and competence of the individuals in the team needs to be of professionally recognised standing.

B3.5. HOW DOES THE TEAM REPORT INTO THE SAFETY MANAGEMENT SYSTEM?

Integrity management and inspection form part of the overall safety management process. The team is expected to contain someone with reporting links and the ability to feedback information and concerns to other safety bodies.

B3.6. DOES THE TEAM HAVE WIDER INDUSTRY KNOWLEDGE?

In the key areas it is desirable that there exists a breadth of knowledge and experience from work on other plants and other sites. The Competent Person or other independent parties may be useful in this respect.

B3.7. HOW IS THE ‘COMPETENT PERSON’ INTEGRATED IN THE TEAM?

Within the Pressure Systems Safety Regulations 2000, the Competent Person is used in connection with three distinct functions – to advise Duty Holders on the scope of examinations, to draw up or certify the written scheme of examination and to carry out and report the examination in an appropriate manner. The Competent Person thus has an important role in ensuring an appropriate balance of risk for which a wider knowledge of the causes of equipment failures together with an appreciation of accident scenarios is an advantage. Good communication between

Competent Persons and technical support staff within their corporate organisations is required.

B3.8. HOW DOES THE TEAM RECORD MEETINGS AND DECISIONS?

As risk assessment is best undertaken as an interactive process, the team needs to have a number of meetings at the different stages. It is useful to have written records of these meetings to enable auditing of the decision making process.

B3.9. IS ACCESS TO STAFF, EXPERTS AND OTHER RESOURCES ADEQUATE?

Team leaders must have the necessary seniority and authority to call upon sufficient financial and manpower resources as required. Organisational independence of team leaders from the pressures of the production function is highly desirable to maintain objectivity.

B3.10. WHAT ARE THE TEAM'S TERMS OF REFERENCE?

The team must know its terms of reference, the purpose and the objectives of the inspection, and the necessary rigor of its approach. When undertaken rigorously, qualitative risk assessment is very acceptable and beneficial. In many cases, the information required for quantitative risk assessment either does not exist or is not sufficiently accurate.

B4. ASSEMBLY OF THE PLANT DATABASE

B4.1. WHAT ESSENTIAL DATA IS USED FOR INTEGRITY MANAGEMENT BY RBI?

Essential data for integrity management by risk based inspection should include: original design, construction and installation data and drawings, reports of previous inspections, reports of modifications and repairs, reports of changes of use, operating procedures, conditions and records, and maintenance procedures and records.

B4.2. ARE PLANT RECORDS ACCURATE AND COMPLETE?

If accurate or complete records have not been maintained, then there is uncertainty, and the assessed risk increases. This could result in more inspection being required.

B4.3. HAS THE DATA BEEN VALIDATED?

Whenever possible, 'essential data' should be validated within a recognised quality assurance system. Hearsay, assumptions and postulations should be treated with caution and due allowances made for possible error.

B4.4. HOW WELL ARE THE OPERATING CONDITION/ENVIRONMENT KNOWN?

Duty Holders have a responsibility to know and monitor the operating conditions and environment of their equipment. Many pressure vessels have been found to operate under conditions for which they were not designed, for example, fatigue and high or low temperatures. Adverse environment, either inside or outside the equipment, can increase corrosion rates and susceptibility to cracking (e.g. chloride in sea water locations).

B4.5. WHAT DATA RELATING TO PLANT RELIABILITY AND FAILURE HISTORY IS AVAILABLE?

Data from maintenance reports, shutdowns and equipment failures should be available and taken into account in the RBI planning process. The condition of replaced equipment and the time to failure may provide a valuable guide to deterioration rates. Investigations of the causes of repeated plant shutdowns and plant failure may indicate weaknesses within the system that could be having other detrimental effects.

B4.6. WHAT INFORMATION RELATING TO FAILURE CONSEQUENCES IS AVAILABLE?

The plant database should contain the information necessary to assess the consequences of failure. This might include assessments of stored energy and pressure, inventories of chemicals, toxicity or flammability data, details of employee proximity and local population, climatic conditions, information about local rivers, wildlife and the underlying geology, business risk analyses etc.

B5. ANALYSIS OF ACCIDENT SCENARIOS, DETERIORATION MECHANISMS, RISKS AND UNCERTAINTIES

B5.1. HAS THE DUTY HOLDER ADDRESSED ALL THE STAGES OF THE RISK ANALYSIS?

A risk analysis requires all six stages in the process to be completed:

- Identification of accident scenarios involving failure of the equipment
- Identification of potential deterioration mechanisms and modes of failure
- Assessment of the probability of failure from each mechanism/mode
- Assessment of the consequences resulting from equipment failure
- Determination of the risk from equipment failure
- Risk ranking and categorisation

B5.2. WHAT APPROACH TO RISK ANALYSIS IS THE DUTY HOLDER ADOPTING?

Duty Holders may take undertake risk analysis using any of the following approaches: qualitative, semi-quantitative and fully quantitative. Whatever approach is taken, it needs to be appropriate for the type of equipment and validated. The risk analysis must identify the likelihood of equipment failure and the relevant consequences.

B5.3. WHAT ACCIDENT SCENARIOS INVOLVE EQUIPMENT FAILURE?

An accident scenario is a sequence of events that could cause failure of equipment leading to further detrimental effects and consequences. Different methods are available to assist Duty Holders identify accident scenarios. When considering initiating events, the possibility of unlikely but credible circumstances should be taken into account.

B5.4. HOW ARE DETERIORATION MECHANISMS AND FAILURE MODES IDENTIFIED?

Duty Holders and Competent Persons should be able to show that the processes used for identifying deterioration mechanisms and failure modes are sufficiently wide ranging and systematic. Acceptable processes could include:

- Review of plant history and information from previous inspections
- Review of generic experience across similar industries or plants
- Elicitation of expert knowledge of structural integrity and materials
- Check lists in the form of published tables
- Computer based expert systems

There are many different deterioration mechanisms and modes of failure associated with pressurised systems. These include failure of protective devices, corrosion/erosion, creep and high temperature damage/cracking, fatigue cracking, stress corrosion cracking, hydrogen blistering, embrittlement and brittle fracture, buckling and damage. Descriptions are available in the literature.

B5.5. HOW HAS THE LIKELIHOOD OF FAILURE BEEN DETERMINED?

Whatever method Duty Holders choose to apply for assessing the likelihood (frequency) of failure, the assessment must take into account of all potential deterioration mechanisms and failure modes and their threat over time. It should be noted that the likelihood of failure is increased when there is lack of knowledge or uncertainty about the equipment, its history, operation and predicted condition. Qualitative descriptive categories (such as very unlikely) should be defined by specified criteria.

B5.6. WHAT FACTORS DETERMINE THE CONSEQUENCES OF FAILURE?

When assessing the consequences of failure resulting from failure of pressure equipment, Duty Holders must take account of the energy and type, amount and rate of product released from the system, and other relevant factors. The assessment should evaluate the potential for releasing one or a combination of the following: flammable substances, steam and hot gas, toxic substances, high pressure liquid/gas, missiles, pipewhip, and equipment displacement. The proximity of people and the threats to their Health and Safety and damage to other systems and the environment are key aspects that must be evaluated.

B5.7. WHAT ARE THE RISKS OF FAILURE?

The risk of failure is the product of the likelihood and consequences of failure and may be described in either qualitative or quantitative terms. There may be separate risks associated with different types of consequences. Various measures are available for quantifying risks to Health and Safety of the individual employee and of the general public.

B5.8. HOW ARE THE RISKS OF DIFFERENT ITEMS RANKED AND CATEGORISED?

Risk ranking and categorisation should identify the relative risk of failure from different items of equipment and different categories of risk. The could include:

- Equipment with a known and active deterioration mechanism
- Equipment with a high frequency but low consequences of failure
- Equipment with high consequences but a low frequency of failure
- Equipment where there is lack of key data or uncertainty

In each case, action is required to manage the risk through on-line monitoring, periodic inspection, sample inspection, more frequent or intensive inspection, improved design, material, operations and training as appropriate.

B6. DEVELOPMENT OF THE INSPECTION PLAN WITHIN THE INTEGRITY MANAGEMENT STRATEGY

B6.1. WHAT MEASURES DOES THE INTEGRITY MANAGEMENT STRATEGY CONTAIN?

The integrity management strategy should contain appropriate measures to manage and limit the risks of failure of which inspection through a written scheme of examination is normally a part. Depending on circumstances, other measures might include material sampling, leakage detection, pressure testing, continuous monitoring of the operating conditions and operator training etc.

B6.2. DOES THE WRITTEN SCHEME COVER ALL PARTS DEFINED BY THE REGULATIONS?

Under the Pressure Systems Safety Regulations 2000 (PSSR), every pressure system requires a written scheme of examination covering all relevant parts of the system. These parts are identified as all protective devices, every pressure vessel and every pipeline and pipework where a defect would give rise to danger. Other systems containing hazardous materials may also require a scheme of examination as a means to comply with the COMAH Regulations.

Parts may be excluded from regular examination within the scope of the written scheme where a defect would not give rise to danger. Instances could include where deterioration is not anticipated, where the stored energy is low and the contents innocuous, or where the equipment is installed in a location as not to constitute danger in the event of a failure. The written scheme should identify these parts and justify the exclusion on the basis of the risk assessment in every case.

B6.3. WHAT DETERMINES THE EXAMINATION OF NEWLY INSTALLED EQUIPMENT?

New and second-hand equipment should normally be examined following installation and before the equipment is used for the first time. The extent and form of this examination depends on the level of conformity assessment of design and fabrication, and the results and effectiveness of inspections made during fabrication, installation and previous service. The Competent Person will confirm the form that this examination will take when drawing up or certifying the written scheme.

B6.4. HOW DOES THE TIMING OF THE FIRST EXAMINATION REFLECT THE RISK?

Equipment must be judged to have a higher likelihood of failure before favourable operating experience is demonstrated by the first in-service inspection or by other means. The timing of the first examination should take account of aspects such as:

- The level of conformity assessment of the design and manufacture
- Tolerance to inadequate design or manufacture.
- Uncertainty about the actual operating environment

Risk ranking can be used to prioritise the timing of the first examination.

B6.5. WHAT METHODS AND FACTORS ARE USED TO SET INSPECTION INTERVALS?

The maximum interval between examinations for equipment within a written scheme should be based on established approaches using historical experience, industry guidelines, or a proportion of calculated remnant life. Duty Holders may, with the agreement of the Competent Person, adjust the interval between examinations so that the risk of failure is appropriately low having taken all relevant factors into account. Examination intervals should have a degree of conservatism (factor of safety) commensurate with the potential uncertainties and limitations in the information available and the assessed risk of failure.

A wide range of factors relating to the likelihood and forewarning of failure should be taken into account when setting examination intervals. Factors to be taken into account are given by the HSC Approved Code of Practice (ACoP) issued in support of the PSSR 2000 and should include:

- Known or postulated deterioration mechanisms
- The rate of deterioration
- Tolerance to defects during future operation
- Uncertainties (particularly in the current condition and degradation rate)

B6.6. DO SCHEMES FOR INSPECTING SIMILAR ITEMS CONFORM WITH HSC ACoP?

The HSC Approved Code of Practice to the PSSR 2000 states that items within a group of similar equipment must be treated for examination as individual items within the written scheme. A form of staged examination is permissible within the bounds set by the written scheme for each item. The written scheme for each item may be modified after each examination and account taken of favourable operating experience gained from other items in the group that have had greater duty.

B6.7. HOW ARE SPECIFIC WELDS AND SITES FOR EXAMINATION IDENTIFIED?

Schemes for sample examination of welds should be based on a ranking according to their relative risk of failure. Duty Holders should be expected to know the locations of welds where the likelihood of defects is highest.

B6.8. HOW ARE EXAMINATION METHODS LINKED TO POTENTIAL DETERIORATION?

Duty Holders should select examination methods whose effectiveness and reliability to detect and characterise potential deterioration and defects that could threaten fitness-for-service has been demonstrated.

B6.9. WHAT INSPECTION STRATEGY APPLIES TO HIGH FAILURE CONSEQUENCE EQUIPMENT?

The safety of high failure consequence equipment can benefit from periodic spot checks for unanticipated deterioration.

B7. ACHIEVING EFFECTIVE AND RELIABLE EXAMINATION

B7.1. ARE THE SELECTED NDT METHODS/TECHNIQUES APPROPRIATE FOR THE DETECTION AND ASSESSMENT OF THE DAMAGE MECHANISMS ANTICIPATED?

In selecting the NDT methods/techniques, consideration should be given to the description of the deterioration mechanism sought (its location, orientation etc.) Another important consideration is the size of the deterioration that must be reliably detected; this may be based on either existing acceptance standards or fitness-for-purpose criteria.

B7.2. ARE THERE INSPECTION PROCEDURES AVAILABLE WHICH SATISFACTORILY COVER THE RANGE OF EQUIPMENT/WELD GEOMETRIES TO BE EXAMINED?

It is important that the inspections to be carried out are covered by a written inspection procedure. The procedure should address the following aspects: details of the inspection technique, personnel requirements, equipment details, calibration details, scanning details, sensitivity and recording levels, reporting requirements, safety considerations and any pre-requisites e.g. surface preparation requirements, access requirements etc.

B7.3. DO THE INSPECTION PERSONNEL HAVE THE APPROPRIATE TRAINING AND QUALIFICATIONS FOR THE TASKS TO BE CARRIED OUT?

Details of personnel training and qualification requirements should be stated in the inspection procedure. For the main inspection and NDT methods, approved training courses and PCN, CSWIP or ASNT certification is available. For the specialist or remote inspection techniques, training is usually available from the equipment manufacturers.

B7.4. WHAT CHECKS ARE BEING CARRIED OUT TO ENSURE THAT THE INSPECTION EQUIPMENT IS FUNCTIONING CORRECTLY?

It is important that inspection equipment is checked regularly. Details of the checks to be carried out should be stated in the inspection procedure. In the case of the ultrasonic method, for example, it is quite common to see BS 4331:Part 1 referenced in an inspection procedure. This standard specifies the on-site checks that are required to ensure the ultrasonic test equipment is functioning correctly.

B7.5. IS INSPECTION QUALIFICATION REQUIRED FOR HIGH-RISK EQUIPMENT?

Inspection qualification is applicable when the safety or economic consequences of inadequate inspection are severe. It is particularly necessary when the inspection method(s)/techniques(s) are new and not covered by existing standards/certification, and also when the inspection is likely to be problematic, as a result of complex geometry, difficult materials etc. Inspection qualification improves confidence and involves the formal assessment of procedures, equipment and personnel using a combination of technical justification and practical assessment (usually carried out on a representative test piece(s)).

B7.6. IS EVIDENCE OF NDT CAPABILITY AVAILABLE (PARTICULARLY FOR NON-INVASIVE, LONG RANGE AND ACOUSTIC EMISSION INSPECTION TECHNIQUES)?

For all inspections, evidence of the capability of the NDT or other technique employed should be available. For the more straightforward inspections this could be a simple document that states the capability to detect and size certain flaw types with reference to independent published data. For newer and more specialist techniques, such as the non-invasive, long range and acoustic emission techniques, a more comprehensive document is expected as these techniques remain largely unproven with little reference data available in the published literature. The Duty Holder should either (in order of preference) (i) carry out their own capability evaluation or (ii) obtain equipment manufacturers capability statements.

B7.7. IS COMPATIBILITY WITH PREVIOUS INSPECTION RESULTS BEING MAINTAINED?

This is to facilitate assessment of equipment degradation from NDT results. It is important that this is addressed, particularly if the inspection technique being applied differs significantly from the technique(s) used for previous inspections of the equipment.

B7.8. ARE INSPECTION DATUMS AND CO-ORDINATE SYSTEMS ON THE COMPONENT BEING MAINTAINED FOR FUTURE INSPECTIONS?

This is important when data between successive inspections is to be compared.

B7.9. HOW ARE INSPECTION RESULTS DOCUMENTED AND ARCHIVED?

Proper documentation and archiving is important to facilitate comparison of data between successive inspections. It is particularly important if there is likely to be a long period between successive inspections or when there is the possibility that personnel involved in previous inspections may no longer be available.

B8. ASSESSMENT OF EXAMINATION RESULTS AND FUTURE FITNESS-FOR-SERVICE

B8.1. HOW HAVE EXAMINATION RESULTS BEEN ASSESSED?

Under the PSSR, the Competent Person takes responsibility for the quality and assessment of examination results. The assessment should determine the current condition of the equipment, changes from the design condition, the condition as initially fabricated, and the condition at the last inspection. The effectiveness and reliability of the examination methods used should be taken into account in making these assessments.

B8.2. WHAT ASSESSMENT OF FITNESS-FOR-SERVICE HAS BEEN MADE?

Evidence of the assessment of fitness-for-service is expected by reference to design specifications, fitness-for-service calculations or other means. The assessment should be based on the current condition and predicted changes in condition during the operating period until the next scheduled examination. Equipment is normally fit-for-service providing it is predicted to remain within the minimum design basis allowed by the initial code of construction. Recognised methods for assessing the fitness-for-service of equipment containing defects have been published by the American Petroleum Institute (API 579), British Standards (BS 7910) and British Energy (R6).

B8.3. HOW HAS UNCERTAINTY IN THE DATA BEEN ADDRESSED?

The data upon which fitness-for-service assessments are made needs to be verifiable and conservative. Sensitivity studies or the use of partial safety factors are recommended where data is uncertain, particularly when small changes could affect the assessment. Deterioration rates and rates of defect growth can be extremely variable and increase non-linearly with time.

B8.4. WHAT MEASURES HAVE BEEN TAKEN TO ADDRESS RISKS FROM DETERIORATING EQUIPMENT?

As a result of the assessment of fitness-for-service, the Competent Person may recommend that equipment is replaced, modified, or repaired, or that the operating conditions are changed to reduce the risk of failure. Replacements, modifications, repairs, or changes to operating conditions should be completed by a set date or immediately if there is imminent danger.

B9. FEEDBACK FROM INSPECTION

B9.1. WHAT PROCEDURES ARE IN PLACE TO DRIVE THE FEEDBACK PROCESS?

Procedures within the Duty Holder's organisation are expected to ensure feedback of the examination results and fitness-for-service assessment into the plant database so that a re-assessment of the risk and the inspection plan can take place. A requirement for feedback and re-assessment should normally be included within the written scheme of examination. There should also be procedures to enable feedback into the plant database of information about excursions and events during operation that could affect the risk assessment.

B9.2. IS NEW KNOWLEDGE IDENTIFIED WITHIN THE PLANT DATABASE?

As part of the feedback process, new knowledge about the condition of the plant should be incorporated within the plant database. Information about the initial and previously assessed condition should be retained so as to enable trends to be determined.

B9.3. IS THERE EVIDENCE OF FEEDBACK BEING CARRIED OUT?

Following an inspection, documentary evidence should be available to show that a re-assessment of the risk and the inspection plan has been made.

B9.4. WHO IS INVOLVED IN THE RISK RE-ASSESSMENT?

The composition of the team carrying out the risk re-assessment should be approximately the same as that which carried out the initial assessment and should follow the same guidelines. It should be expected that one individual would act as the focal point for gathering feedback from inspections, operational issues and any other aspect affecting the risk.

B9.5. DOES THE INSPECTION PLAN REFLECT CHANGES IN THE RISK ASSESSMENT?

Outcomes from the re-assessment of risk can vary from no action being necessary to a fundamental revision of the inspection plan depending on how well the predicted condition matched the examination results. Under the PSSR 2000, the Competent Person will determine whether the scheme of examination is still suitable, or whether it should be modified, and will set a date defining the maximum interval until the next inspection. When a re-assessment has changed the initial assessment of the risks, a report detailing the reasons and consequences of the change is expected.

B9.6. DOES GOOD COMMUNICATION EXIST BETWEEN PLANT OPERATORS AND THE RISK ASSESSMENT TEAM?

It is important that good communication exists between the plant operators and the risk assessment team. This is to ensure that any changes to operating limits or operating practice or inspection intervals recommended by the assessment team are communicated and implemented.

B10. AUDIT AND REVIEW OF THE INTEGRITY MANAGEMENT PROCESS

B10.1. HOW OFTEN IS THE MANAGEMENT PROCESS AUDITED AND REVIEWED?

The whole process of integrity management, inspection planning and implementation is expected to be periodically audited and reviewed. Often this is carried out as part of the regular check on the quality system and Health and Safety management. Intervals between audits are a matter for organisations to decide (considering the rate of changes in the industrial, organisation, regulatory and operating environments), but a maximum period of five years is suggested.

B10.2. WHO CARRIES OUT THE AUDIT AND REVIEW?

An independent body internal or external to the company should carry out the audit. The auditing body needs to be independent of the personnel normally responsible for integrity management. Quality assurance managers or senior Health and Safety managers can often fulfil this role.

B10.3. WHAT ASPECTS OF THE MANAGEMENT PROCESS ARE COVERED?

The audit should establish that the integrity management process exists and is properly designed, is being operated at all stages, and is effective at meeting its objectives. The guidance for successful Health and Safety management published by the Health and Safety Executive (HSG(65)) is applicable. The following list indicates the aspects that should be covered within a typical audit:

- Objectives
- Allocation of responsibilities, accountability and resources
- Co-operation, communications and competence
- Risk analysis and inspection planning
- Implementation of inspection
- Measuring, reviewing and auditing performance of the whole process

B10.4. IS DOCUMENTARY EVIDENCE AVAILABLE TO SUPPORT EACH ASPECT?

Auditing the performance of organisations requires documentary evidence to be made available. Integrity management by risk based inspection is no exception and evidence is required to cover all stages of the process. As the scope of RBI is wide, the amount of documentary evidence needed to support the management of process may be large.

B10.5. HOW HAS THE INTEGRITY MANAGEMENT PROCESS CHANGED?

Audits are designed to provide assurance of successful management and where necessary identify weaknesses and recommend improvements. Changes and improvements in the integrity management process brought about by audit need to be identified and evidence provided of successful implementation.

APPENDIX C

TECHNIQUES FOR IDENTIFYING ACCIDENT SCENARIOS

TECHNIQUES FOR IDENTIFYING ACCIDENT SCENARIOS

Hazard and Operability Studies (HAZOP)

HAZOP is a structured brainstorming exercise by a team discussion designed to identify potential variations and deviations from the design or operating intent and their consequences. A list of guidewords is sometimes used to stimulate the discussions. Typically, these focus initially on credible variations of process parameters (flow, level, temperature) before branching out to consider human factors and less likely ‘what if’ scenarios.

HAZOP is a procedural tool designed to highlight and identify hazards and operability problems in industrial plants that could reduce the plant’s ability to achieve productivity in a safe manner. Studies tend to be wide-ranging and threats to the integrity of pressure systems may only be considered briefly. This procedure is a powerful tool for hazard analysis and its methodical approach ensures that weaknesses in the design intent are detected and acted upon.

Failure Modes and Effects Analysis (FMEA)

FMEA is a qualitative structured method for identifying the immediate effects of failure at the component level. It is implemented by considering each item of equipment and associated systems in the plant, detailing the possible failure modes (e.g. leak or break in the case of pressure equipment), and determining their resulting effect on the rest of the system. The analysis is more concerned with the specifying the likely effects and criticality of different modes of failure rather than the mechanisms or events leading to the failure.

It is a simple method that is easy to apply, yet it is a powerful tool that can be used to improve the quality of products and processes. It can lead to focussing on consequences and additional safeguards to mitigate the effects of the failure. It is common for individuals familiar with system functionality to perform FMEA, but teams of experts can produce greater insight into the mechanisms and wider range consequences.

Fault Tree Analysis (FTA)

Fault tree analysis (FTA) is a logic-based methodology that is used for identifying and analysing the events that could lead to an accident or other undesirable outcome. The technique is one of ‘reverse thinking’ where the analyst begins with the final undesirable event that is to be avoided and identifies the immediate causes of that event. The aim of the analysis is to determine the chains or combinations of preceding events and circumstances.

Tracing the chain of events leading to the final outcome can indicate where extra monitoring, regular inspection and protective devices such as temperature and pressure sensors and alarms, could protect and forewarn impending failure. By analysing failure data and assigning probabilities to each preceding event, the probability of the final outcome occurring can be determined.

Fault tree analysis is a very useful tool for studying the routes by which an accident can occur, and is particularly effective at identifying accident scenarios due to secondary and tertiary causes. It requires a great deal of skill and effort to implement. For this reason it is expected to be used only by industries where the consequences of failure could be very severe.

Event Tree Analysis (ETA)

Like FTA, event tree analysis is also a logic based methodology for identifying accident scenarios, but unlike FTA it is forward thinking. The analysis begins with a given initiating failure event and develops the resulting sequence of events, normally over a short time interval, making assumptions about the availability or otherwise of safeguards and back-up systems such as protective devices. ETA is an extension of failure modes and effects analysis to cover the whole system.

Event trees are valuable for examining the consequences of failure. They are less effective for the analysis of the causes of system failure. The short timescale over which events are considered may mask longer term consequences such as the gradual deterioration of equipment due to faults elsewhere.

Human Reliability Analysis (HRA)

HRA was introduced as a means of quantifying the interaction between human and engineering systems. It aims to improve the understanding of the contribution made by all people to engineering systems. It is a systematic evaluation of the factors that influence the performance of all personnel such as operators, maintenance engineers, technicians etc, and is normally undertaken as a group activity.

APPENDIX D

TYPES OF DETERIORATION AND MODES OF FAILURE OF PRESSURE SYSTEMS AND CONTAINMENTS

TYPES OF DETERIORATION AND MODES OF FAILURE OF PRESSURE SYSTEMS AND CONTAINMENTS

- **Failure of the Protective Devices**

Many boilers and other pressure vessels have failed through over-pressure as a result of the pressure relief system valves or bursting discs being ineffective. Periodic inspection and maintenance procedures should detect problems such as fouling or incorrect adjustment. The position and potential to isolate protective devices from pressure systems should be checked as part of the procedures, particularly after plant modifications or maintenance.

- **Corrosion/Erosion (general, local, pitting)**

Wall thinning due to corrosion or erosion is common and can occur by a variety of mechanisms including simple rusting, aqueous chloride, high temperature sulphidation, vapour liquid impingement etc. Wall thinning may be general over the surface, localised to certain areas or the presence of pitting. Where a plant item may be subject to internal or external corrosion or erosion, the current thickness of material should be determined and reviewed against the original design values and previous inspection results to ascertain the rate of thinning.



Fig.D1 General corrosion of external surface of pipework

When wall thinning due to corrosion or erosion is detected, the position and rate of thinning needs to be established to enable the implications to be assessed using an accepted methodology (e.g. BS 7910 or API 579). A certain amount of thinning may be tolerable in a plain membrane area whereas the same thinning in areas subject to direct loading, such as saddle points, may be a cause of concern. The degradation rates, established from the inspection results, should be used to predict

the residual life of the plant. Rates of corrosion and erosion can be extremely variable and depend on the local process conditions. They are not necessarily constant with time. Care is therefore needed in assessing and predicting rates.



Fig.D2 Localised corrosion pitting of internal surface of finned pipework

- **Creep and High Temperature Damage**

Creep and other high temperature damage modes occur in steels at temperatures above 350°C and particularly above 450°C. Creep is time dependent with microscopic voids eventually leading to macroscopic cracks and crack growth.

The amount of creep damage before macroscopic cracking can be determined by techniques such as replication.

High temperature plant operating under creep conditions should not normally be operated beyond the creep design life unless the scope of inspection has been amended to take that into account. Since failure can occur at pressures less than the set pressure of an associated protective device, the safe operating limits should state the remaining life in relation to maximum permissible pressure and temperature, for example:

Maximum permissible pressure = 44 barg
Maximum permissible temperature = 440°C
Remaining life = 52560 hours

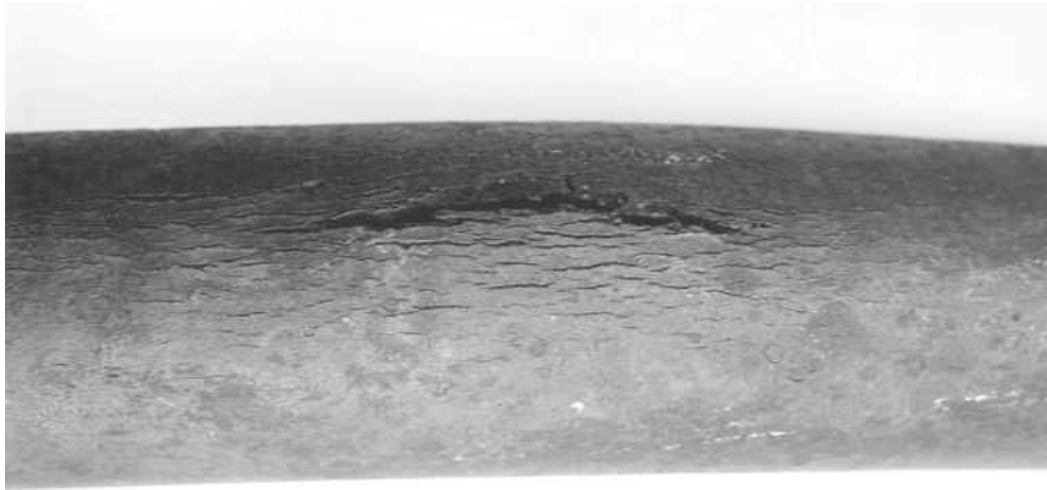


Fig.D3 Creep fissure in pipework wall

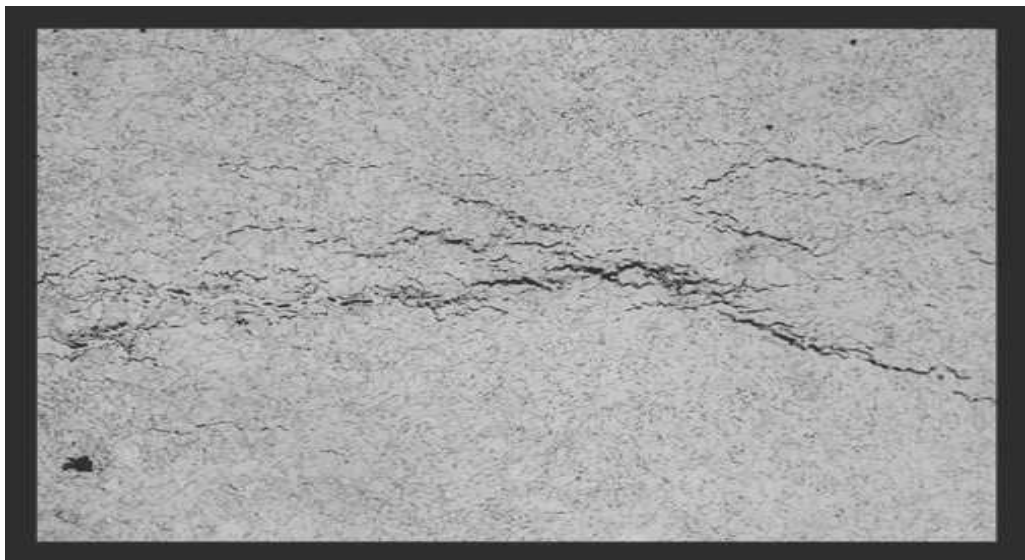


Fig.D4 Microscopic detail of creep damage

Fatigue

Fatigue cracking is caused by loading creating a cyclic or varying stress. Fatigue damage first occurs at a micro-structural level before manifesting itself as a macroscopic crack, and a further period of crack growth may occur before failure. Areas where there can be high cyclic stress, such as stress concentrations at the toe of welds or areas subject to rapidly and frequently varying temperatures, are particularly susceptible.

Certain factors can increase the likelihood of defect initiation and/or growth rate and can include environmentally assisted mechanisms such as corrosion and localised high concentrations of chlorides, shape imperfections in a welded joint such as misalignment and undercut, the application of post weld heat treatment and the combination of the amplitude and frequency of the applied stresses.

Since failure due to fatigue cracking can occur at pressures less than the set pressure of associated protective devices, the safe operating limits should be stated in terms of the number of fatigue cycles and details of the stress fluctuations, for example:

Cyclic pressure range = 27 barg

Permissible number of remaining cycles = 4200

Number of cycles/year = 700



Fig.D5 Fatigue damage of shaft

- **Stress Corrosion Cracking (SCC)**

SCC occurs in specific material/environment combinations e.g. carbon steel/ammonia, stainless steel/chlorides. The susceptibility of the materials of construction, including welds and heat affected zones, to SCC from either internal or external sources should be considered.



Fig.D6 Stress corrosion cracking in vessel shell



Fig.D7 Microscopic detail of stress corrosion cracking

- **Embrittlement**

There are four main embrittlement modes: temper, caustic, hydrogen and hydrogen sulphide.

- Temper embrittlement applies to carbon steels at temperatures between 375°C and 575°C.
- Caustic embrittlement is a form of SCC of carbon steels by concentrated hydroxides at temperatures greater than 70°C.

- Hydrogen embrittlement of steels occurs in hydrogen service at hydrogen partial pressures greater than 5 bar and elevated temperatures.
- Hydrogen Sulphide embrittlement or sulphide stress cracking occurs in susceptible materials at H_2S partial pressures greater than 0.05 psia.

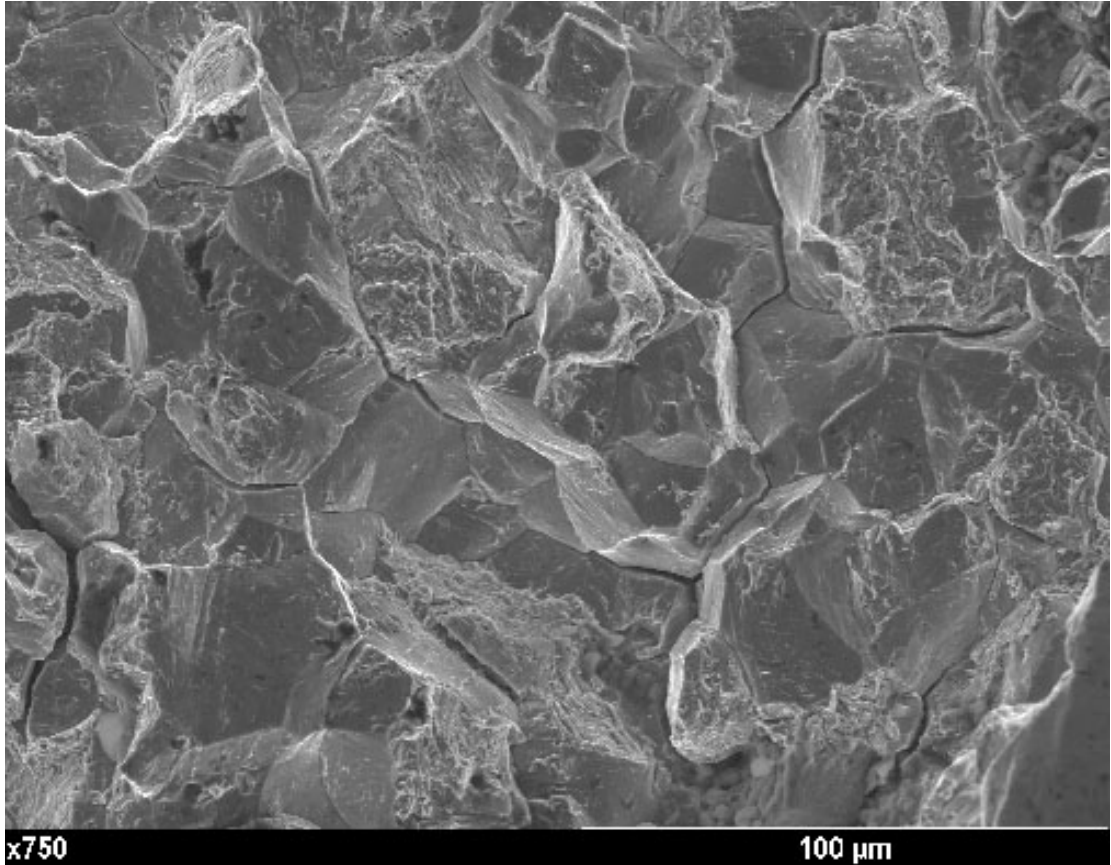


Fig.D8 Microscopic detail of hydrogen embrittlement

- **Hydrogen Blistering/Stepwise Cracking**

These failure modes are hydrogen in steel phenomena where hydrogen is promoted to enter the steel by cathodic poisons such as H_2S , HCN and HF.

- **Brittle Fracture**

An item of carbon steel plant that can operate safely up to the relief valve set pressure at temperatures in excess of $0^\circ C$ may not be able to tolerate the same pressure at the lowest working temperature if this lies below $0^\circ C$. Material ductility reduces and cleavage fracture becomes more likely as the temperature is reduced. Transition temperatures can vary widely, depending on the grade of steel is important that the correct steel is selected if low temperature service is envisaged or is a possibility.

Unlagged vessels without internal heating of the contents can reach temperatures below $0^\circ C$ during a normal British winter, as can lagged vessels containing fluid in a gaseous form. Most liquefiable gases such as Chlorine or Ammonia etc can cause the metal temperature to be reduced below $0^\circ C$. It is for these reasons that the

maximum permissible pressure must be calculated as a safe operating limit for the lowest working temperature below 0°C.

Brittle fracture can also result from certain operating conditions such as blow down of contents which causes local chilling even when bulk temperatures are above 0°C.

Material may be brittle for reasons other than that of operating at low temperature. Poor microstructure or mechanical properties as a result of incorrect heat treatment or material composition are also common causes. Brittle failures have been known to occur, due to the use of incorrect or unsuitable weld processes and welding consumables.

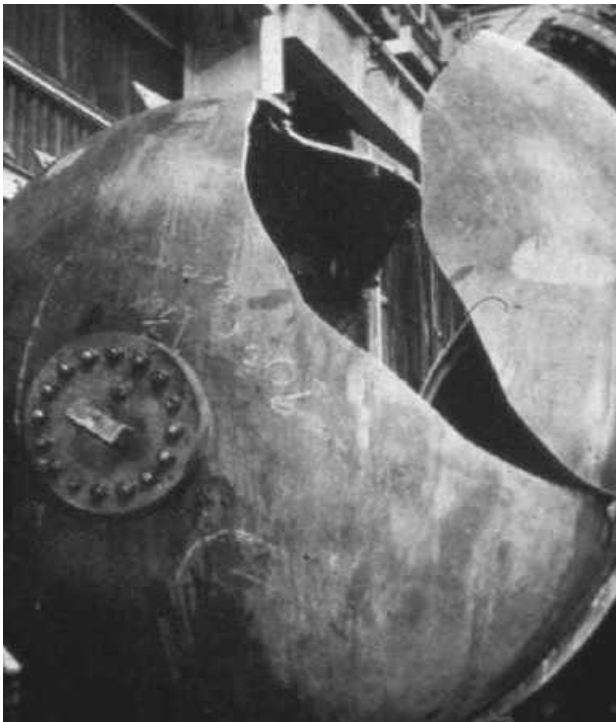


Fig.D9 Brittle fracture of vessel under hydraulic test conditions

- **Buckling**

Collapse by buckling as a result of external pressure can be devastating. Although not covered by the Pressure Systems Safety Regulations, this particular failure mode should not be overlooked. Reduction in net section area of members loaded in compression and by external pressure can create weakness and reduce the critical load.

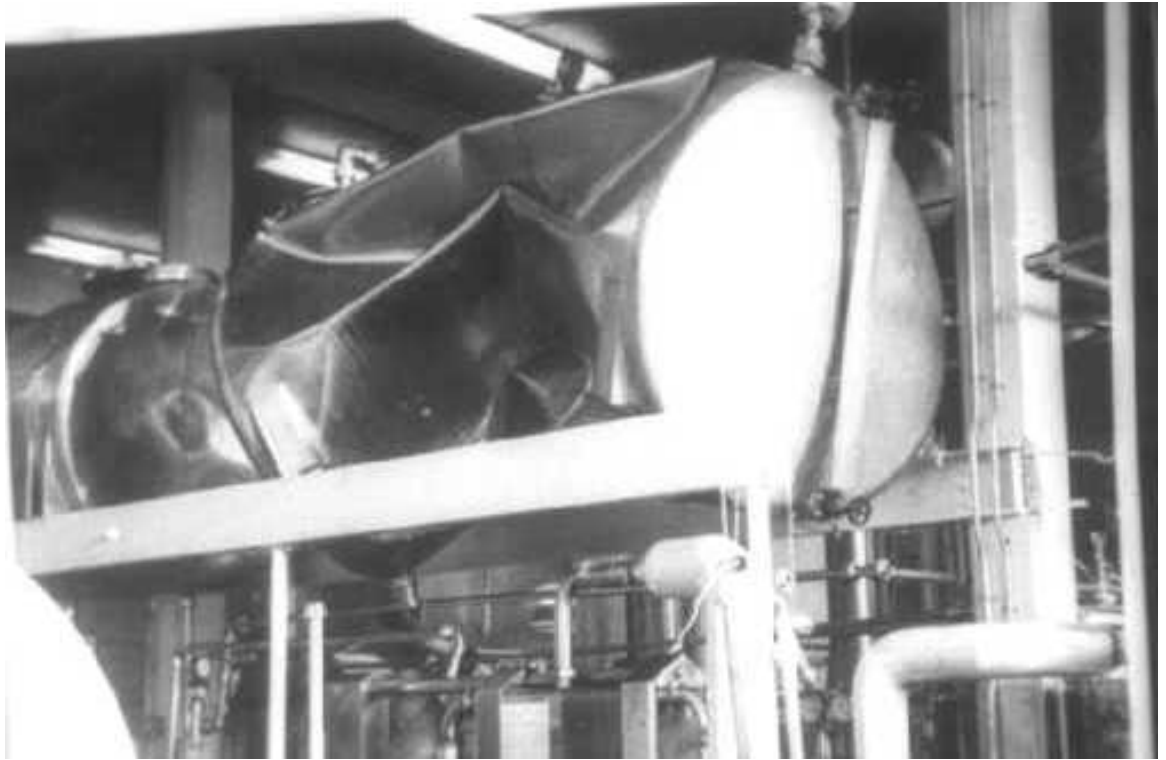


Fig.D10 Vessel collapse due to vacuum conditions

- **Potential Damage Mechanisms for Refinery Equipment**

The American Petroleum Institute is to publish in its document API 571 (Potential Damage Mechanisms for Refinery Equipment) a set of tables cataloguing deterioration mechanisms, manufacturing defects and failure modes encountered in refinery equipment and the circumstances in which these can occur. The tables relate the process conditions (temperature, environment, flow, stress, impact damage) to the materials of construction and the type of fabrication. These tables are not claimed to be all-inclusive, but will be probably the most comprehensive compilation that will be available.

APPENDIX E

SOFTWARE PACKAGES SUPPORTING RISK BASED INSPECTION OF PRESSURE SYSTEMS AND CONTAINMENTS

SOFTWARE PACKAGES SUPPORTING RISK BASED INSPECTION OF PRESSURE SYSTEMS AND CONTAINMENTS

Akzo Nobel – Risk Based Inspection (RBI) Program

The basis of this program is a 5 x 5 risk matrix with the consequence of failure being based on:

- a) Cost of repair, replacement etc
- b) Environmental issues
- c) Safety
- d) Critical downtime

The likelihood of failure is based on the calculation of an integrity factor (S):

$$S = \frac{D_{\text{last}} - (CR \times I) \times U}{D_{\text{min}}}$$

Where:

- D_{last} = last measured condition (mm)
- CR = degradation rate (mm/year)
- I = inspection interval (year)
- U = uncertainty factor
- D_{min} = minimal condition (mm)

To decrease the likelihood of failure the integrity factor (S) needs to be increased i.e.

- Decrease I , intensifying the inspection programme
- Increase D_{last} e.g. replacement/renewal of equipment
- Decrease CR by using other materials or amending the operating conditions
- Decrease U by using more reliable inspection techniques
- Decrease D_{min} by fitness-for-purpose techniques

Det Norske Veritas (DNV) – Risk Based Inspection (RBI) Program

DNV were involved with the API in the development of the RBI methodology outlined in API 581 – Risk Based Inspection Base Resource Document, and their program follows the methodology detailed in that document.

The likelihood analysis relies on a database of generic failure frequencies for refining and chemical processing equipment. This generic data is then modified by two terms, the Equipment Modification Factor (F_E) and the Systems Evaluation Factor (F_M) to arrive at a more realistic frequency:

$$\text{Freq}_{\text{adjusted}} = \text{Freq}_{\text{generic}} \times F_E \times F_M$$

These modification factors reflect identifiable differences between various items of plant. The Equipment Modification Factor examines details specific to each item and to the environment in which the item operates whilst the Systems Evaluation Factor adjusts for the influence of the facility's management system on the mechanical integrity of the plant.

The consequence analysis establishes the outcome of leaks from the system in terms of effect on People, Lost Production, Equipment Damage and Environmental Pollution.

The Welding Institute (TWI) – RiskWise

On the basis of historic inspection, maintenance and operation the Likelihood and Consequence scores are computed for each equipment item/damage mechanism by the consideration of several likelihood factors and consequence factors.

For each equipment item/damage mechanism, the likelihood score at time t:

$$L(t) = DMF(t) \times (LF_1 + LF_2 + LF_3 + \dots)$$

Where DMF = damage mechanism factor and LF = likelihood factor.

For each equipment item, the total consequence score:

$$C = FMF \times (CF_1 + CF_2 + CF_3 + \dots)$$

Where FMF = failure mode factor and CF = consequence factor

These factors are then translated into a 5 x 5 matrix to obtain the overall risk value.

The inspection frequency is determined by reference to the failure likelihood rating.

Tischuk – T-OCA (Operational Criticality Assessment)

T-OCA is a comprehensive risk based integrity management system which includes elements to assess the risk, plan inspection and maintenance and a scenario builder that allows an assessment of the effects of change.

The program uses a simple 3 x 3 matrix in the assessment where the consequences of failure is assessed using eight criteria covering operational, economic, safety and environmental issues and the likelihood of failure is assessed using models for failure mechanisms appropriate for each equipment type.

The results from the risk assessment are converted to an inspection and maintenance plan based on user defined matrix of tasks and frequencies.

A 'what if' tool is provided where the effects of change on the risk assessment are assessed and allows the user to see the effects of changes in materials of construction, operating conditions, process composition or the passage of time on the risk assessment outcome.

LMP Technical Services Limited – PRIME: RBI Module

This software program is provided as a module to an asset management system.

Each relevant plant item is assessed against an established set of consequence criteria based on stored energy, safety (Health and Environment), replacement costs and consequential loss and probability criteria based on design/operational life and operating life/conditions with the results being plotted on a 3 x 3 matrix.

It is acknowledged that whilst the matrix provides a reasonable guideline as to the extent of the risk it will be necessary for the Competent Person to consider these results in relation to the plant item.

Once this level of risk has been established then the item is placed in a 'ladder of frequency', which gives 4 steps in examination periodicity based on the SAFed guidelines.

This grading is based on:

Frequency 0: Set for new installed systems, no historical evidence, rate of deterioration high and/or unpredictable.

Frequency 1: At least 1 previous inspections, rate of deterioration moderate

Frequency 2: At least 2 previous inspections, rate of deterioration low

Frequency 3: At least 3 previous inspections, rate of deterioration low

e.g:

	Frequency 0	Frequency 1	Frequency 2	Frequency 3
Periodicity:	26 months	48 months	60 months	72 months

It will require the authority of the Competent Person to confirm any changes in frequency of examination as other factors may need to be taken into account.

APPENDIX F
GLOSSARY OF TERMS

GLOSSARY OF TERMS

The following gives a glossary of the meaning of terms used in this report.

Accident Scenario

An accident scenario within risk based inspection is a set of circumstances that could give rise to deterioration and failure of equipment, and the subsequent events causing detrimental effects and consequences

Competent Person

The Competent Person is a term defined by the Pressure Systems Safety Regulations and means a competent individual person (self-employed) or a competent body of persons (corporate or unincorporate) with the attributes and responsibilities defined by the Regulations.

Consequences

The consequence of failure through the unintentional release of stored energy and hazardous material is the potential for harm. This may be harm to the Health and Safety of employees and/or the public, pollution and other environmental damage, business costs such as lost production, repair and replacement of equipment or the loss of the company reputation. All these can be measured in different ways.

Damage

Within this report, damage refers to a detrimental macroscopic change in the condition of the equipment, for instance dents, gouges, bulging, normally as a result of discrete events such as impact or fire.

Defect

A defect is an unacceptable macroscopic metallurgical imperfection. The term 'defect' is narrower than 'flaw', and refers to imperfections that may be cause for rejection of a weld or component.

Degradation

Degradation in equipment refers to a detrimental metallurgical change in the material. It includes embrittlement, hydrogen attack, and creep before macroscopic manifestation of a flaw.

Deterioration

In this report, 'deterioration' in equipment is a detrimental change from its design condition as a result of damage, defects or degradation.

Duty Holder

Within this report, the term ‘Duty Holder’ is used to refer to the owner or user of a pressure system or containment of hazardous material. The Duty Holder has duties relating to safety and periodic examination of the system or containment. For pressure systems, these duties are specified in the Pressure Systems Safety Regulations 2000.

Examination

Examination is a means of determining the condition of equipment. It may include non-destructive testing, such as ultrasonic testing and radiography, as well as visual surveys, replication, and material sampling etc. Examination might also include leak or pressure testing (for pressurised components) or other test of functionality.

Failure

Within this guidance, any unintentional release of stored energy and/or hazardous contents from a pressure system or containment constitutes a failure. Failure usually involves a breach in the containment boundary and a release of contents into the environment. In extreme cases, stored energy may be released as a high pressure jet, missiles, structural collapse or pipe whip and contents may be flammable and/or toxic.

Fitness-for-Service Assessment

Fitness-for-service assessments are quantitative engineering evaluations of the structural integrity of a component containing a flaw or damage. Published procedures available for fitness-for-service assessment include API 579 (for equipment in the refining and petrochemicals industry), BS 7910 (for metallic structures containing flaws) and R6 (developed by the UK nuclear industry).

Flaw

Any macroscopic metallurgical imperfection involving a discontinuity such as a crack, solid inclusion, gas pore etc.

Hazard

A ‘hazard’ is an intrinsic property or disposition of anything to cause harm. It is conceptually distinct from ‘risk’ because it makes no reference to the probability that harm will occur. A wider discussion of this distinction is given in the HSE discussion document ‘Reducing Risk Protecting People’ (Paragraphs 36 to 41).

Inspection

In general, inspection is a process of verifying conformity with a written requirement and can be carried out at a number of levels. Within this guidance, the term ‘inspection’ refers to the planning, implementation and evaluation of

examinations and/or testing to determine the physical and metallurgical condition of equipment in terms of fitness-for-service.

Non-Destructive Testing (NDT)

Non-destructive testing is an operation which covers the inspection and/or testing of any material, component or assembly by means which do not affect its ultimate serviceability.

NDT Method

Any method of examination of materials, components, and assemblies, which does not affect their ultimate serviceability. It categorises the physical principle of examination, i.e. ultrasonic, radiography, liquid penetrant etc.

NDT Technique

The specific way in which the NDT method is applied. For ultrasonic testing this might mean pulse-echo, tandem, TOFD, focused probes and so on, or the combination of these which has been adopted.

NDT Procedure

A definition of how NDT is implemented for a specific test situation; a written description specifying all essential NDT parameters and setting out the precautions to be observed when applying an NDT technique, following an established standard, code or specification.

Pressure System

Within this report, a 'pressure system' is that referred to by the Pressure Systems Safety Regulations as containing a relevant fluid (pressure > 0.5 bar). Viz:

- a. A system comprising one or more pressure vessels of rigid construction, any associated pipework and protective devices
- b. Pipework with protective devices to which a transportable pressure receptacle is or is intended to be connected
- c. A pipeline and its protective devices

Probability of Failure

The probability of failure of an item of equipment is mean frequency with which the specified failure event would be expected to occur in a given period of time, normally one year.

Qualitative Risk Analysis

Qualitative risk analysis is based primarily on engineering judgements. The likelihood and consequences of failure are expressed descriptively and in relative terms.

Quantitative Risk Analysis

In a quantitative risk analysis, the probability and consequences of equipment failure are determined for each accident scenario from the underlying distributions of the variables using reliability analysis methods.

Risk

The risk of failure of an item of equipment combines the probability of failure (mean failure rate) with a measure of the consequences of that failure. If these are evaluated numerically, then the risk is defined as the product of the probability of failure and the measure of consequence. There can be different risks for different measures of consequence.

Risk Analysis

Within this report, a 'risk analysis' is a process of analysing the risk of failure that should contain the following stages:

- Identification of accident scenarios involving failure of the equipment
- Identification of potential deterioration mechanisms and modes of failure
- Assessment of the probability of failure from each mechanism/mode
- Assessment of the consequences resulting from equipment failure
- Determination of the risk from equipment failure
- Risk ranking and categorisation

Risk Based Inspection

Risk based inspection is a process that involves the planning of an inspection on the basis of the information obtained from a risk analysis of the equipment.

Risk Matrix

A risk matrix is a Cartesian map with increasing likelihood of failure on one axis and increasing consequences of failure along the other. Often the likelihood and consequences axes are divided into broad bands. Risk is presented as a position or region within the map corresponding to the particular combination of likelihood and consequences.

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