HSE

Health and Safety Executive

Plant ageing

Management of equipment containing hazardous fluids or pressure

Prepared by
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for the Health and Safety Executive
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Management of equipment containing hazardous fluids or pressure

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The purpose of this report is to increase awareness of the factors to consider when managing equipment containing hazardous fluids or pressure, and to help those responsible for equipment to understand and assess the risks of accumulated damage and deterioration. The information is at a general rather than an equipment-specific level, and can be applied to a wide range of static equipment and associated machinery.

The management of equipment begins with an awareness that ageing is not about how old the equipment is, but is about what is known about its condition, and the factors that influence the onset, evolution and mitigation of its degradation. Once the symptoms of ageing are understood, and detected from inspection, a decision can be made how to proceed. The options can include putting together a case to justify continued service, re-rating, repair, or scrapping the equipment.

In addition to the engineering aspects, there are important managerial issues that should also be considered. The company culture and defined roles and responsibilities are discussed in relation to managing equipment. These are affected by staff demographics, along with skills, training and competencies. The importance of maintaining documentary information and records throughout equipment life is also highlighted.

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The content of this report is based on the opinion of the authors and does not necessarily constitute HSE policy. The authors of this report bring a range of disciplines and experience to the production of this report, including asset management, structural integrity, materials and corrosion, welding engineering, inspection and non-destructive testing, and insurance and risk management.

"AGEING IS NOT ABOUT HOW OLD YOUR EQUIPMENT IS; IT'S ABOUT WHAT YOU KNOW ABOUT ITS CONDITION, AND HOW THAT'S CHANGING OVER TIME"

THIS PLANT WAS ONLY ABOUT 5 YEARS OLD, BUT DUE TO POOR MAINTENANCE WAS STAINED IN MANY LOCATIONS FROM ACID SEEPAGE. THIS MADE IT HARD TO INSPECT AND TO KNOW HOW IT WAS AGEING.

THESE PRE-WAR RIVETED PRESSURE VESSELS REMAINED IN GOOD CONDITION AND SUCCESSFULLY OPERATED IN SERVICE UNTIL THE 1990'S

PLANT AGEING: MANAGEMENT OF EQUIPMENT CONTAINING HAZARDOUS FLUIDS OR PRESSURE

PREFACE

The purpose of this report is to increase awareness of the factors to consider when managing equipment containing hazardous fluids or pressure, and to help those responsible for equipment to understand and assess the risks of accumulated damage and deterioration. The information is at a general rather than an equipment-specific level, and can be applied to a wide range of static equipment and associated machinery.

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In addition to the engineering aspects, there are important managerial issues that should also be considered. The company culture and defined roles and responsibilities are discussed in relation to managing equipment. These are affected by staff demographics, along with skills, training and competencies. The importance of maintaining documentary information and records throughout equipment life is also highlighted.

First time readers of this report may wish to start by looking at the contents list to find topics of specific interest, or to go directly to the Audit Tool (Appendix 1) on page 105. The Audit Tool summarises much of the information in a list of 17 questions for consideration. A series of case studies in Appendix 2 provides practical illustrations of some of the information.

The report is offered to industry and regulators as an aid to assist their own thinking rather than as prescriptive practice. It is to encourage good and efficient management and will be revised as required to reflect experience.

Finally, the authors would like to thank all the many individuals and organisations that have contributed to the development of the report. They also acknowledge the support of the Health and Safety Executive.

CONTENTS

1 AWARENESS OF AGEING

1.1 HOW CAN THIS REPORT HELP YOU?

"Ageing is not about how old your equipment is; it's about what you know about its condition, and how that's changing over time". There is an increasing amount of equipment containing hazardous and/or pressurised fluids in UK industry that is at risk from age-related deterioration and damage (ageing). Many companies are seeking to maximise the life of their plants and fewer installations are being replaced. This report will help you to identify the risk of ageing equipment, and to manage it to ensure that it stays safe and reliable.

Your company may wish to operate equipment beyond its original design life or to repair or re-use equipment or to assess fitness-for-service and remanent life, but finds it difficult to achieve the right balance between assuring safety and cost-driven operation. It might benefit from knowing more about the risks and effects of ageing, recent trends for asset management, and new technologies for maintenance, inspection, assessment and repair. In addition to considering technological issues, the report also addresses the softer management, people and competence issues that companies face in keeping equipment under control. This report has been prepared to support you deal with these issues. Figure 1 illustrates some of the factors about ageing equipment to consider.

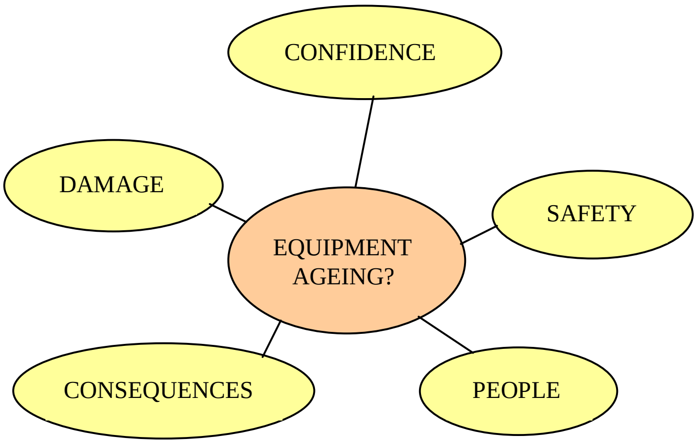

Figure 1 Factors to think about when equipment could be ageing

You may find this report is particularly useful for managing equipment at high-hazard mechanical installations, such as found in the chemicals, power and process industries. It is applicable in part to a much wider range of safety critical equipment across industry, where avoiding loss of containment and unplanned outages are the main aims. Businesses of all sizes can benefit from this report. Following the report will help you to meet your obligations under Health and Safety Regulations.

The report will assist equipment owners, users and operators, maintenance, inspection and insurance companies, organisations employing Competent Persons, technical consultancy organisations, and regulators such as the Health and Safety Executive (HSE). Significant experience in the management of ageing equipment across a range of industrial sectors has been incorporated in the report. Comment has been included from a range of users, inspectors and regulators to improve the relevance of the report for the conditions and constraints under which the businesses that use equipment containing hazardous fluids currently operate.

1.2 PURPOSES OF THE REPORT

1.2.1 General Aims

The aim of the report is to help you to manage and ensure the safety of ageing equipment containing hazardous fluids and/or pressure. It recognises the business and regulatory environment that many owners and users of equipment now operate under, together with the constraints that these impose. The ideas put forward are intended to be safe, practicable and cost effective. The report is to help you think about how best to manage ageing assets, rather than proposing any prescriptive way.

In particular the report aims to:

- Improve the management of your organisation and people for ageing equipment.
- Highlight indicators and risk factors to enable you to identify the risk of ageing.
- Help you plan maintenance and inspection of your equipment with the appropriate techniques, procedures and periodicity and to record what has been done.
- Explain non-destructive testing techniques that can enable you to measure and assess the effects and rate of ageing, and hence determine safe operating limits, and appropriate monitoring measures.
- Assist you in assessing the remaining safe life of equipment, for example, in cyclic service, in corrosive environments, or if ageing damage is found.
- Provide information and practical examples through case studies on the organisation, management and human factors involved in ensuring safety of ageing equipment.
- Provide an audit tool for you to determine whether the standards of managing ageing equipment are adequate.

The report complements the HSE report on ‘Best Practice for Risk-Based Inspection as a Part of Plant Integrity Management’ [F3], published on the HSE website in 2001. This document has been recognised as providing valuable information on the application of risk assessment to inspection planning, but does not deal specifically with the issues of ageing equipment.

1.2.2 Who Will Find The Report Useful

The report is aimed to assist everyone with a responsibility for the operation and safety of equipment containing hazardous fluids and/or pressure in all sectors of UK industry. These include owners and users, and their authorised representatives with the responsibility for operating and maintaining the safety of the system. Others with responsibility include plant operators, process engineers, maintenance, inspectors and NDT personnel. The report will enable these people to recognise the signs of ageing and what action needs to be taken.

The report will also be of value to engineering surveyors and Competent Persons involved in the approval of schemes of examination and setting examination periods and safe operating limits. Whilst there is considerable practical experience in this field, the report may be a useful checklist, and provide a structured approach to assess how well equipment is being managed. The experience contained in the report will also help those new to the role.

HSE Inspectors will find the report particularly useful when auditing industrial premises and installations. In particular, the audit tool will help them to ask pertinent questions. The report will help them know what to look for during inspection visits.

The report is written in a form intended to be useful and accessible across industry. In addition to the obvious high hazard industries such as oil production, refining and chemicals, the report also addresses the needs for equipment in other industries where the process hazards may be perceived to be lower, such as cryogenic equipment, steam raising equipment, air receivers and food processing equipment. The principles of managing containment equipment can also be applied to many other types of industrial plant (e.g. rotating machinery).

Parts of the report will be useful to the user of small general pressure plant or the small company where the volume of hazardous fluids held is relatively low. While complex information and management systems may not be appropriate, the general principle that the management of the equipment needs to be proportionate to the level of hazard applies. The report will help you meet the obligations of Health and Safety Regulations and to know when to call in professional advisers.

1.2.3 Assisting Compliance With Health And Safety Regulations

This report applies to the management of equipment containing hazardous and/or pressurised fluids, which will normally be related to fulfilling duties and responsibilities under one or more of the following health and safety regulations. The report will assist you in fulfilling these responsibilities, but it is not intended to be specific to any particular regulation. Where applicable, you should consult the regulations below, together with their Approved Codes of Practice and Guidance (see Section 1.5.2).

(a) Health and Safety at Work etc Act 1974 (HSW Act) – general safety legislation that applies to everyone concerned with work activities.

(b) Pressure Systems Safety Regulations 2000 (PSSR) - covering all on-shore steam systems and other pressure systems operating in-service above 0.5 barg [A3].

(c) Pressure Equipment Regulations 1999 (PER) – implementing the European Pressure Equipment Directive for pressure equipment placed on the market [A2].

(d) Control of Major Accident Hazard Regulations 1999 (COMAH) - covering the control of major accident hazard sites with safety critical equipment [A4].

(e) Provision and Use of Work Equipment Regulations 1998 (PUWER) [A6].

(f) Pipeline Safety Regulations 1996 (PSR) [A10].

(g) Offshore Installations and Wells (Design and Construction etc) Regulations (1996) [A11] – covering equipment used off-shore that is exempt from other regulation.

1.2.4 Structure And Content Of The Report

After this introduction, the report is in three self-contained parts plus four Appendices.

- Section 2 discusses some of the asset management issues faced by companies with potentially ageing equipment. These include the roles and responsibilities of the people involved, company culture, strategies and systems for asset management and the retention of knowledge, and human factors such as ensuring competency in the workforce, supply issues and training and certification.

- Section 3 deals with ways of identifying that equipment is damaged through ageing, or has reached a stage in life when there is high uncertainty of whether damage is present. It considers the life cycle of equipment in relation to the "bath-tub" failure rate curve and describes equipment life in four stages. Key indicators and risk factors as symptoms or conditions of ageing or for premature ageing are given. There is a substantial part on the approach to inspection at different stages of life and on detecting and sizing damage from different NDT techniques.

- Section 4 considers the options available when damage due to ageing is detected. It covers the assessment of fitness-for-service and safe operating limits for different types of damage, and the determination of extended remanent life. Issues relating to the repair of ageing equipment are discussed. There is information on revalidation of equipment after repairs and modifications, changes to operating conditions, and the use of second hand equipment. Finally, the report discusses the decision of when to take equipment out of service on economic grounds.

- The Appendices include the audit tool question set with a commentary (designed so that it can be used as a stand-alone document). There is a series of case studies illustrating aspects of the management of ageing equipment covered in the main text. Extended information on the approach to inspection and the capabilities/limitations of various NDT methods is also provided.

The detailed contents page will help you to find your way around the report. References between Sections are made forward and back within the document. Many of the terms and abbreviations used in the report are defined in Section 1.5.1 A list of useful references is given in Section 1.5.2 and these documents are cited throughout the report with their letter-number reference.

Some of the issues relating that are covered in this report are shown in Figure 2.

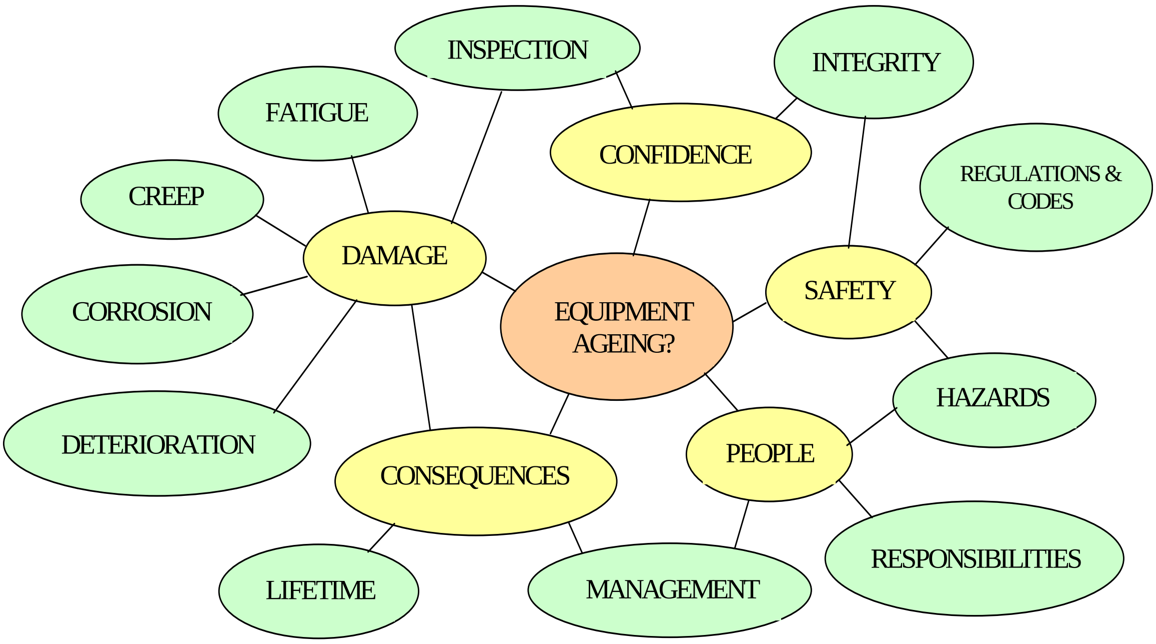

Figure 2 Issues discussed by this report for the management of ageing equipment

1.3 WHAT'S THE CONCERN?

The quotes below illustrate that some organisations and individuals are not recognising or acting on the signs of ageing. There is a large amount of practical experience and technical knowledge now available. New methods for the detection, measurement, assessment, monitoring and repair of ageing damage have been developed; and there is clearly a need for greater awareness of these. Until this report, this experience and awareness has not been available within a single accessible published document.

"There haven't been any problems up to now, so the equipment is safe, isn't it?"

One concern is that some companies simply do not know what condition their equipment is in, nor how its condition has been changing over its lifetime. Sometimes the possibility of ageing damage occurring over the equipment's lifetime has not even been considered.

"We don't have any drawings for this vessel; and we don't know what the material is"

Before the end of the equipment's design life, the person who has been responsible for managing the integrity of a piece of equipment (the 'Responsible Person') could have retired, and the company may not have been able to replace them. Important information about the equipment can be lost. In some cases, information about equipment may never have existed:

"It's only been in service for two years so it can't be ageing."

A misconception is that ageing damage only occurs after a long time in service. However, if the equipment is poorly constructed, maintained, or undergoes changes in its service conditions, it can start to age right from day one. Equipment remains in-service for which no code limit on the number of fatigue cycles or corrosion allowance has ever been evaluated, or for which the evaluated limit has been reached. For some pressure vessels, the fatigue limit may be as little as 500 cycles. Some equipment may have been designed with a short expected lifetime.

"The integrity of our equipment is separate from our safety management"

The integrity of equipment containing pressure or hazardous fluids is often the first line of defence in preventing a release of potentially damaging energy or substances. Yet in some companies there is insufficient thought about how the integrity of the equipment is proactively managed to ensure risks of failure are sufficiently low. The management of equipment integrity is an essential part of the safety management system.

"Our equipment does not contain defects"

Even equipment that has been inspected and found to be 'defect-free' after fabrication may later contain defects that have formed while the equipment has been in service. A recent survey for the HSE by the Safety Assessment Federation (SAFed) of the causes and frequency of defects detected in pressure systems in-service found that many defects were ageing related. Another recent HSE study of hydrocarbon leaks on offshore installations found that equipment degradation was the main cause. The prevalence of fatigue cracking in vessels, corrosion of piping, and cracking of low temperature systems was of particular concern.

"We maintain and inspect only equipment to meet the Pressure Systems Regulations"

All equipment that contains a hazardous fluid or pressure needs to be appropriately maintained and inspected according to the potential hazard. While pressure systems require a written scheme of examination under the Pressure Systems Safety Regulations 2000 (PSSR), other equipment containing hazardous fluids sometimes does not receive attention due in order to meet the requirements of other health and safety regulations. Pressure systems that contain fluids that are hazardous for reasons in addition to the stored energy may require management measures that go beyond those of PSSR 2000.

1.4 WHAT EQUIPMENT THE REPORT COVERS

1.4.1 Equipment Categories And Types

The report applies to the management of the following categories and types of equipment where they contain pressure and/or hazardous fluids:

- Pressure vessels and reactors.
- Columns, distillation systems.
- Heat exchangers, boilers, and steam systems.
- Vacuum vessels.
- Piping and pipework.
- Flexible hose assemblies, connectors.
- Pressure relief devices.
- Pumps and valves and other process plant.
- Air receivers.
- Refrigerated systems.
- Jacketed vessels, autoclaves.
- Storage tanks, storage spheres.
- Fixed drums and other containers.

In addition to the above equipment containing hazardous fluid and/or pressure as part of normal operation, you should also consider equipment that may contain a hazardous fluid or pressure temporarily or as part of a planned emergency response. Equipment supporting or welded to the containment boundary must also be considered where failure of this equipment could affect the containment boundary (see Case Study 1). Other related equipment therefore includes:

- Supporting structures such as hangers, legs, and saddles.
- Building structures and foundations.
- Drip trays, bunds and drains.
- Flare stacks, chimneys and drains for venting.
- Insulation, linings and protective coatings.
- Protective features and buildings.

The report is primarily intended to apply to fixed equipment and installations. Mobile and transportable systems and equipment, including gas cylinders, storage drums, transportable pressure containers, compressors, and road and rail tankers, have integrity management requirements that may go beyond the scope covered in this report. Much of the advice given in the report will be applicable to these types of equipment, but may not be sufficient to ensure integrity.

In the process industries, machines are typically used to move or effect a physical change on process fluids (e.g. pumping, stirring, agitating, impelling etc). Internal flow velocities are often higher than those in the associated static equipment, and the accumulation of potentially significant stress cycles is more common. Typically, containment of the process fluids is dependent on integrity of both static components (e.g. casing) and dynamic components (e.g.

shaft and sliding or rotating seal). These kinds of machines, and their rotating parts, fall within the scope of the report, but their variety limits any specific treatment.

Whilst the basic deterioration mechanisms are the same for both static equipment and machines, the latter are more complex and generally have a higher failure rate. However, such failures are less frequently associated with sudden loss of containment, and as such, tend to be less catastrophic. In most cases, the integrity management of machines is covered by general legislative requirements such as Provision and Use of Work Equipment Regulations 1998 (PUWER) rather than the more specific requirements that apply to pressure systems (e.g. PSSR 2000).

1.4.2 Hazardous And Pressurised Fluids

When a fluid (gas or liquid) is pressurised, potential energy is stored in the fluid and the containing system, which, if released, has the potential to create a hazard, such as an explosion, projectiles, pipe-whip, or a fluid jet. A pressure system, defined in the PSSR 2000 [A3], is generally one or more fixed pressure vessels of rigid construction with any associated pipework and protective devices containing a relevant fluid. It may also be pipework intended to be connected to a transportable pressure container, (e.g. a gas cylinder), or a pipeline and its protective devices containing a relevant fluid.

A relevant fluid means a liquid or gas (including steam) that is at a pressure greater than 0.5 bar above atmospheric. Remember that PSSR 2000 are intended to guard against danger from the release of the stored energy within the pressure system. They do not necessarily cover dangers from other hazardous properties of the fluid for which additional measures may be necessary.

There can also be systems containing fluids with stored energy outside the system that do not fall under PSSR 2000. These could include high volume storage tanks or tanks and piping where fluid could be released from a height. Even if the fluid is not in itself hazardous (e.g. cold water) you should consider the level of hazard from a potential leak or break, including the effect on other adjacent equipment, and decide what management of this equipment is required.

Contained fluids can be hazardous for reasons separate to and/or in addition to stored energy. Toxicity and flammability are two hazards that need particular consideration. Both hot and cold fluids can be hazardous, and the report has relevance for steam and hot water, and refrigerated (cryogenic) equipment, as may be found, for example, in the food and drinks industry.

The hazards from the release of steam at high pressure are often not recognised, yet should be treated with the utmost seriousness. When steam leaks through a crack or opening, anyone in its path can suffer scalds, severe burns or organ damage. A high-pressure steam jet can cut through human tissue. Steam systems, including boilers, steam generators and piping, are common, frequently extensive, subject to ageing mechanisms.

Contact with cryogenic fluids, (such as liquefied gases or cooled oil/organic liquids or refrigerant), can also be severe. Frostbite, burns, and damage to organs can result. When cryogenic liquid spills onto steel structures, the rapid local quenching induces low temperatures and high stress that increase the risk of cracking and brittle fracture. You should remember that the rapid depressurisation associated with the sudden escape of pressurised gas through a narrow orifice, such as a vent, safety device or leaking joint, reduces its temperature. Gases stored at ambient temperature, and thus the containing equipment, can become cryogenically self-cooled if rapidly depressurised.

Hazardous fluids include dangerous substances as defined in the Dangerous Substances and Explosive Atmospheres Regulations 2002 (DSEAR) [A7]. Dangerous substances are flammable or highly oxidising by their nature, or in the way they are used, and have the potential to cause fires or explosions. Typical examples are petrol and petroleum products (such as white spirit and organic chemicals) and hydrocarbon gases (such as methane, ethylene, propane and butane (LPG)) and oxidising agents (such as hydrogen peroxide and oxygen), as well as certain dusts.

Another category of hazardous fluid are those defined in the Control of Substances Hazardous to Health Regulations 1994 (COSHH) and the Integrated Pollution Prevention and Control Regulations [A8, A9]. Even small releases of dangerous carcinogens and chemicals can be lethal. Systems containing asphyxiating gases and liquids, such as ammonia and chlorine, pose a significant health risk if not properly managed. The presence of heavy metals in process fluids, such as those found in the plating industry, and substances such as hydrogen fluoride are very hazardous if released. These potential hazards are common in the pharmaceuticals and chemicals industry, but may also be found in many other kinds of industrial processing.

The CHIP Regulations (Chemical Hazard Information and Packaging for Supply) Regulations) 2002 require suppliers of substances to classify them into certain categories of danger. The criteria used are set out in the Approved Classification and Labelling Guide to CHIP 2002. Many dangerous substances and substances hazardous to health are listed and this is a good reference to determine if your substance is hazardous or potentially hazardous.

Chemical carryover from a process and the effects of flow can have a strong influence on corrosion and erosion. In some plants, a lack of knowledge of the chemical constituents of process streams, residues and waste can be problem. Good knowledge and control of the hazardous fluid inventory are important.

In using this report, you are advised to consider where hazardous fluids and fluids under pressure may exist, and consider the equipment that contains them, as part of the assessment of ageing. The integrity of that equipment is the first and maybe the only line of defence from a dangerous release. Knowing how that equipment ages, both from the fluid contained and the external environment, is key for ensuring safety.

1.4.3 What Is Ageing Equipment And What Kind Of Equipment Is At Risk?

Ageing equipment is equipment for which there is evidence or likelihood of significant deterioration and damage taking place since new, or for which there is insufficient information and knowledge available to know the extent to which this possibility exists.

The significance of deterioration and damage relates to the potential effect on the equipment's functionality, availability, reliability and safety. Just because an item of equipment is old does not necessarily mean that it is significantly deteriorating and damaged. All types of equipment can be susceptible to ageing mechanisms, and it is worth drawing attention to some examples.

(a) Piping and pipework systems

Piping and pipework are, statistically, the source of most leaks and loss of containment in systems containing hazardous fluids or pressure. Hydrocarbon leaks in particular have been identified as a major threat to safety both off and on-shore. However, piping and pipework systems are often excluded from inspection under schemes of examination, even when a risk assessment has been carried out, and for this reason may not be inspected over long periods of time.

In some instances, the risk assessment may only consider the hazard from the release of stored energy and neglect the other hazards from the release. In other instances, risk assessments of releases from piping and pipework systems may never be made. Even if safety may not be compromised, the lack of knowledge and possibility of deterioration become real, and from the view of asset management and reliability the position may eventually become unsatisfactory.

If not properly managed, piping and pipework can be susceptible to damage from corrosion (internal and external), erosion, fatigue, creep, ratchetting, leakage from gaskets, loose fittings, loss of insulation or protective coatings, mechanical damage, internal scaling or fouling. Fatigue of small-bore attachments can be a particular problem where there is vibration from rotating equipment or flow-induced vibration. Good management of the risks from ageing piping and pipework is therefore a priority.

(b) Flexible hoses

Flexible hose assemblies (FHAs) are complex components, often under high pressure, and are extensively used for a variety of purposes where failure would create a hazard. Proper lifecycle management and the assurance of personnel competency are important. The UK Offshore Operators Association (UKOOA) has published Guidelines on the management and inspection of flexible hoses [C1].

(c) Protective devices

Safety valves, bursting discs, level gauges, pressure relief equipment including vent lines and stacks and other devices are vital means for protecting equipment against overpressure and are often an indicator of problems elsewhere in the system. However, protective devices are prone to a variety of ageing mechanisms such as fouling, condensation and calibration inaccuracy. Because they are used infrequently, discharge lines can be overlooked, and they require particular attention in any ageing management strategy. Case Study 2 illustrates the consequences when a flare line failed.

(d) Storage tanks

Storage tanks often contain large volumes of hazardous fluids where the consequences of a release are severe. If not properly maintained, tanks can suffer corrosion leading to wall thinning, particularly in unprotected, coastal or damp locations. Where the level of fluid oscillates over a narrow range, the walls of tanks have been known to develop fatigue cracks at the liquid level.

Non-metallic storage tanks (e.g. high-density polyethylene or polypropylene) need to be considered for atmospheric deterioration, as they can become embrittled and crack over a long period in ultraviolet sunlight. The possibility of internal chemical attack should also be considered, as should creep at ambient temperature. Non-metallic tanks are sometimes used to store very high hazard chemicals, such as hydrogen fluoride, and management measures commensurate with the potential risks need to be taken.

Thin walled tanks, as used for example in the food and drinks industry, are susceptible over time to accumulated mechanical damage such as denting and deformation. These can provide a site for fatigue cracking and can reduce resistance to buckling under compressive load or sloshing.

The Engineering Equipment and Materials Users' Association (EEMUA) has published guidelines on the inspection, maintenance and repair of above-ground storage tanks [F5] which forms the basis of introductory and advanced level training on this subject.

(e) Pressure vessels and boilers

Pressure vessels are currently more highly regulated than other types of equipment. They can be subject to a wide range of ageing mechanisms. Like tanks, unprotected vessels are susceptible to corrosion, fatigue and wall thinning, particularly at crevices, external supports and saddles. Liquid impinging onto a surface from a height or passing through a nozzle at high velocity can cause erosion and wall thinning to affected areas. Vibration and fretting of heat exchanger tubes are well known, yet often poorly managed. In heated vessels and boilers, temperature gradients and differences can be a source of thermal fatigue as found, for example, in variable firing boilers. Some heat transfer conditions can result in accelerated corrosion rates.

Apart from boilers, other pressure vessels in common use include those for the storage of hazardous gases under compression, including natural gas, liquid petroleum gas (LPG), ammonia and chlorine. The corrosive potential of ammonia and chlorine is now well recognised, but careful management and inspection of their containment is still required. In contrast, LPG is generally regarded as non-corrosive, but there have been a few instances of LPG tanks found with cracks/corrosion from other sources and contaminants where integrity management has lapsed. The report has relevance for these types of equipment.

Process vessels and columns can have complex life cycles and be subject to multiple, interacting and competing degradation mechanisms. Influencing factors can include the variable composition of chemicals in the feed stock, temperature profile, batch cycling, pressure cycles, and the cleaning process. In general, degradation mechanisms and kinetics can only be determined from a thorough analysis and good inspection data over a sustained period.

It is not possible within this report to foresee all degradation mechanisms. It is only possible to highlight some of the more common mechanisms and those that deserve greater attention. Further examples are given in the case studies in Appendix 2. The main aim is to provide a framework that will help you evaluate the threats to your own equipment for yourself, and take the necessary action.

1.5 ASSOCIATED INFORMATION

1.5.1 Glossary Of Terms And Acronyms

The meanings of some of the terms and acronyms commonly used throughout the report, divided into subject areas, are as follows:

Defined roles and capabilities

Competence: Having and demonstrating the necessary knowledge, skills and experience to do a particular task within a particular context. The individual will have training and experience appropriate to the task, the equipment and the wider circumstances.

Competent Person: Defined by the Pressure Systems Safety Regulations 2000 [A3] to mean a Competent Person (self-employed) or a competent body of persons (corporate or un-incorporate) with attributes and duties defined by the Regulations. These include the preparation and/or approval of written schemes of examination. Other health and safety regulations also specify duties to be carried out by a Competent Person, but these duties and the attributes of the person are different to those defined by PSSR 2000.

Duty Holder: Where the term Duty Holder is used, it usually refers to the person, firm or organisation with the final responsibility for ensuring the safety of equipment under Health and Safety regulation. For pressure systems [A3], the main Duty Holders are the owner (of a mobile system) or the user (of a fixed system). Where pressure systems are supplied by way of lease, hire or other arrangements (e.g. LPG tanks), the supplier of the system can assume the role of Duty Holder for certain regulations. Health and safety regulations covering equipment other than pressure systems define the Duty Holders and their responsibilities differently.

Notified body: A Notified Body is an organisation accredited by a nation state to undertake conformity assessment of products under a European Directive (e.g. PED)

Responsible person: In a non-regulatory sense, is a person with the necessary authority and competence to be responsible for containment equipment covered by this report.

User: The User, as applied to pressure systems or pressure vessels, is the employer or self employed person as the case may be, who has control of the operation of the system or vessel. This definition may also be applied to other types of equipment.

Damage

Ageing: The effect whereby a component suffers some form of material deterioration and damage (usually, but not necessarily, associated with time in service) with an increasing likelihood of failure over the lifetime.

Ageing damage: Within this report, ‘ageing damage’ is term referring generically to types of progressive material damage that could eventually cause equipment failure. Examples of ageing damage are outlined in Section 3.2, including wall thinning due to corrosion etc, cracking, and metallurgical changes. When metallurgical ageing is meant (for example, strain ageing) the term ‘metallurgical ageing’ is used to differentiate this.

Corrosion: Degradation of material due to interaction with the environment leading to a loss of material and/or desirable properties of the material. Corrosion can be general, occur over a wide area, or be localised.

Creep: Continuous permanent deformation of a metal or other material at a load below the yield stress. In metals creep is usually a high temperature phenomenon, while plastics may creep at ambient temperatures.

CUI: Corrosion under insulation. A common corrosion problem associated with older equipment, where moisture trapped within insulation and lagging can cause corrosion of the metal surface underneath.

Damage: A detrimental macroscopic change in the condition of the equipment which can be a symptom of increasing risk of failure or ageing, for instance, dents, gouges, cracking, bulging, thinning.

Defect: A metallurgical imperfection. The term “defect” can be considered narrower than “flaw” and refers to imperfections that may be cause for rejection or failure of a weld or component. See also “Flaw” under “Fitness for Service”.

Degradation: Detrimental change in the material, e.g. corrosion, fatigue, embrittlement, hydrogen attack, and creep (before manifestation of a flaw).

Deterioration: A detrimental change from design or as-manufactured condition influencing the ability of the item to perform the required function.

Erosion: The mechanical removal of material from a surface as a result of relative motion or impact from solids, liquids or vapour. This can be accelerated by the additional effect of corrosion on a surface, and this is known as erosion-corrosion.

Fatigue: Cracking under the influence of fluctuating stresses. These cyclic stresses can occur due to variations in pressure, temperature or other applied loads, and fatigue cracks often occur at stress concentrations. Fatigue crack propagation can continue until the flaw reaches a critical size that results in secondary failure. When fatigue develops with the combined effect of corrosion it is known as corrosion-fatigue.

Hydrogen attack: The reaction of dissolved hydrogen with carbides in ferritic steels resulting in decarburisation and porosity.

Hydrogen blistering/cracking effects: Dissolved atomic hydrogen recombines at inclusions in steels and results in surface blistering or internal cracking (known as Hydrogen (Pressure) Induced Cracking, or HIC/HPIC). When a residual or applied stress is present arrays of internal cracks can combine, which in conjunction with the low ductility, can lead to fracture. This is known as Stress Oriented Hydrogen Induced Cracking or SOHIC.

Hydrogen embrittlement: Loss of ductility in steel and some other alloys due to the presence of atomic hydrogen, often as a result of hydrogen being absorbed by the metal from a suitable environment. This can cause stress corrosion cracking, disbonding of clad corrosion resistant alloy layers, and fabrication hydrogen cracks.

Strain age embrittlement: A loss of ductility (and rise in strength) caused when a low carbon steel is metallurgical aged under sustained stress, time and temperature following plastic deformation (e.g. a dent). The degree of embrittlement also depends on the concentration of elements such as carbon and nitrogen in the steel.

Stress corrosion cracking (SCC): Cracking due to the conjoint action of tensile stresses, and corrosion, neither of which would cause cracking on their own.

Temper embrittlement: Embrittlement of alloy steels caused by holding within, or cooling slowly through temperatures just below the transformation range, typically in excess of 500°C.

Equipment Operation

Consequences: The consequence of failure through the unintentional release of stored energy or hazardous material is the potential for harm. This may be harm to the health and safety of employees and/or the public, pollution or other environmental damage, business costs such as lost production, repair and replacement of equipment or the loss of company reputation. All these can be measured in different ways.

FMEA: Failure Mode Effect Analysis – formal approach to analyse what may go wrong with equipment, and the consequences within a risk framework.

Hazard: Potential for causing harm to people, equipment, or the environment. Within this report this could mean the stored energy of a pressurised system, the toxicity of fluid contained within a vessel, or the consequences of a leakage, such as fire or fumes.

Hazardous fluid: A liquid or gas that could cause a hazard if released. This could be due to its stored energy, toxicity, chemical reactivity, flammability, or temperature.

HAZOPS: Hazard and Operability Study. The results of the study are to ensure that if plant is operated outside the design parameters, there are no unacceptable consequences related to safety or operability.

Maintenance: The act of sustaining or protecting equipment in proper working condition.

Modification: A change or alteration to the equipment's material, design, or operation, such that revalidation should be considered.

Pressure system: Referred to by the Pressure Systems Safety Regulations 2000 [A3] as

- System comprising one or more pressure vessels of rigid construction, any associated pipework and protective devices.
- Pipework with protective devices to which a transportable pressure receptacle is, or is intended to be, connected.
- A pipeline and its protective devices.

and containing relevant fluid (e.g. steam at any pressure or a fluid pressure >0.5 barg).

Remanent life: This is the period of time of an item of equipment, determined by calculation or other means, over which it is safe to use without further assessment.

Repair: To restore to sound condition after damage or deterioration. In general, making repairs introduces changes to the equipment's condition and hence repairs need to be considered as modifications.

Re-rating: The alteration of the operating conditions or safe operating limit of equipment. In the context of avoiding repair or replacement of ageing equipment, the change is usually a reduction of operating pressure (i.e. de-rating). However, equipment can be re-rated for operation at a higher pressure (e.g. change of service).

Safety Management System (SMS): Policy to manage and control risks to health and safety.

Written scheme of examination: A plan for examination of pressure systems that is suitably tailored to the equipment, and reviewed at regular intervals.

Inspection and Non-destructive testing

CUI: Corrosion under insulation. See ‘Damage Mechanisms’

Examination: The whole process of verifying conformity with a requirement for integrity, including planning, inspection, evaluation, and/or leak or pressure testing.

Inspection: A careful and critical scrutiny of the item of equipment for determining its condition, the purpose of which is to discover flaws that can give rise to danger. Inspections can include non-destructive testing, as well as visual surveys, replication of a surface, and materials sampling to determine the physical and metallurgical condition of the equipment.

Non-invasive inspection (NII): Non-destructive testing techniques avoiding the necessity for complete internal access or the removal of insulation or coatings.

Non-destructive testing (NDT): Operation that covers the testing of any material, component or assembly by means that do not affect its ultimate serviceability.

RBI: Risk-based inspection. Approach to inspection planning based on the probability and consequences of failure.

Replication: A technique whereby an imprint is taken of a surface or surface feature (e.g. crack or pit) in order to gain information about the condition of the material.

Fitness-for-service

Damage: See under ‘Damage Mechanisms’

Defect: See under ‘Damage Mechanisms’

Engineering Critical Assessment (ECA): See “Fitness for service assessment”.

Failure: Within this report a failure means an event that results in an unintentional release of stored energy and/or hazardous contents from equipment, usually involving a breach of the containment boundary and release of contents into the environment.

Fitness for service (FFS) assessment: Quantitative or qualitative engineering evaluation of the structural integrity of a component containing a flaw or damage, carried out to a published procedure. Also known as “Fitness for Purpose (FFP) Assessment” or “Engineering Critical Assessment”.

Flaw: Any macroscopic metallurgical imperfection involving a discontinuity, such as a crack, solid inclusion, gas pore etc. See also “Defect” under “Damage Mechanisms”.

HAZ: Heat affected zone. The region in the parent material next to the weld metal that has been metallurgically altered by the heating process of the weld.

PWHT: Post weld heat treatment.

Structural integrity: Equipment or a structure being fit to withstand the service conditions safely and reliability throughout its predicted lifetime.

1.5.2 Organisations Promoting Plant Integrity Management

- **British Compressed Gases Association (BCCA):** A trade body for suppliers and users of compressed gases excluding liquid petroleum gas.
- **British Standards (BS):** The UK organisation for standards and quality.
- **The British Institute of NDT (BINDT):** Professional institution for practitioners of non-destructive testing and plant inspection.
- **Engineering Equipment & Materials Users' Association (EEMUA):** An industry body representing plant operators from a range of industry sectors – the users of engineering equipment and materials.
- **Health and Safety Executive (HSE):** The UK government agency charged with enforcing safety legislation, inspection and providing information.
- **Energy Institute (EI):** An amalgamation of the Institute of Petroleum and the Institute of Energy, the former relating to servicing the needs of the petroleum industry.
- **Institution of Chemical Engineers (IChemE):** Professional institution for chemical, biochemical and process engineering professionals.
- **Institute of Materials, Minerals and Mining (IoMMM):** Professional institution for practitioners of metallurgy, materials science, minerals and mining.
- **Institution of Mechanical Engineers (IMechE):** Professional engineering institution, with Divisions and Groups covering process systems, pressure systems, materials, safety and reliability etc.
- **LP Gas Association (LPGA):** The representative body of the UK LPG Industry dedicated to the safe and effective development of the LP Gas Industry in the UK for the benefit of stakeholders.
- **Safety Assessment Federation (SAFed)**: A trade body comprised of representatives of engineering insurers and Competent Person organisations.
- **UK Offshore Operators Association UKOOA:** An association of companies operating and servicing installations in waters off the UK continental shelf.

1.5.3 Useful References

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6. BS 7608:1993, Code of practice for fatigue design and assessment of steel structures.

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1.5.4 Useful websites

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- Engineering Equipment and Materials Users' Association (EEMUA): http://www.eemua.co.uk/.
- European Pressure Equipment Research Council (EPERC): http://www.eperc.bam.de/.
- Energy Institute (EI): http://www.energyinst.org.uk/.
- Health & Safety Executive (HSE): http://www.hse.gov.uk/.
- Institution of Chemical Engineers (IChemE): http://www.icheme.org/.
- Institute of Mechanical Engineers (IMechE): http://www.imeche.org.uk/.
- JoinIT: http://www.joinit.com.
- Safety Assessment Federation (SAFed): http://www.safed.co.uk/.
- Special Metals: http.www.specialmetals.com.
- United Kingdom Offshore Operators Association (UKOOA): http://www.ukooa.co.uk/.

2 GETTING ORGANISED FOR MANAGING AGEING

2.1 TAKING RESPONSIBILITY AND CONTROL

2.1.1 Owners, Users And Management

As an owner, user or manager of equipment containing hazardous fluids or pressure, you have an overriding responsibility to your employees, contractors, other site residents, the general public, and to the environment for ensuring:

- Health and Safety.
- Minimum impact of operations outside the site.

These responsibilities are effected in terms of:

- Control of Major Accident Hazards.
- Control of Hazardous Chemicals and Dangerous Substances.
- Safe and reliable operation and maintenance of plant and equipment.
- Avoidance of nuisance from operations.
- Minimising waste and discharges.

Failure to comply with health and safety and environmental regulations in these areas can lead to companies and individuals being prosecuted. Enterprises also have responsibility to stakeholders for maintaining production. Directors and senior managers are ultimately responsible and have a particular obligation to:

- Identify and understand the risks.
- Put in place appropriate strategies to manage the risks.
- Set suitable policies, processes and procedures for equipment and operations.
- Delegate agreed responsibilities to competent people and organisations.
- Ensure competency by provide appropriate training and experience.
- Provide adequate resources in terms of time, money, equipment and information.
- Lead communications, co-operation and the management of change.
- Check implementation, close out actions and audit performance.

These obligations are consistent with the principles of a Safety Management System. HSE Guidance Document HS(G)65 describes how a Safety Management System can produce successful health and safety management through setting policy, organisation, planning and implementation, measuring performance, and auditing and review.

The role of the relevant directors and senior management is likely to include the following activities, depending on the nature of the equipment and hazard of products being contained:

- Identification of high hazard installations, plant, systems and equipment.
- Assessment of the major hazards, hazard management policies/methods.

- Setting of Key Performance Targets (KPTs) and Indicators (KPIs) - metrics for measuring and assessing aspects relating to health and safety, reliability, criticality to business etc.
- Assessment of potential impact of failures on employees, business and neighbours.
- Justification of continued ‘Licence to Operate’.
- Investigation of failures and incidents, and information in the public domain.
- Analysis of production impacts / losses from failures and unavailability.
- Authorising improvements as required for continued operation.
- Auditing the management of equipment regularly, to ensure compliance with policies, and implementation of processes and procedures.

In undertaking these activities, there is benefit in involving experienced independent people as well as staff from the plant operations, maintenance and supervisory teams. Some companies appoint a separate Engineering Authority responsible to the Board for asset integrity.

2.1.2 Operators, Maintainers And Supervisors

Many corporate responsibilities for equipment are often devolved to a range of roles in Operations, Maintenance and Site Supervision. Sometimes these roles are out-sourced to separate contracted individuals and organisations. Those ultimately responsible for health and safety have an obligation to set clear requirements and performance standards to operators, maintainers and supervisors, and provide them with the resources to deliver. Operators, maintainers and supervisors, in turn, have the responsibility to comply with the requirements and standards, and to inform those devolving responsibility when compliance is not possible or the resources inadequate.

Operators, maintainers and supervisors will interpret and implement the policies that have been set, and their performance can be measured against Key Performance Indicators on integrity, leakage and releases, reliability and costs. Monitoring equipment performance can be via feedback using operation and maintenance reports, failure and incident reports and modification forms. Depending on the nature of the equipment and the hazards of the products being contained, the role of operators, maintainers and supervisors in respect of the management of ageing includes some or all of the following:-

(a) Communicating within the management hierarchy (both up and down)

- Simple, clear and relevant information exchange – written and verbal.

(b) Control of equipment

- Maintaining a Site Asset Register (or equivalent database) containing key information about equipment (name, location, function, duty, design envelope, maintenance and inspection policy, manufacturer, age).

- Maintenance and protection of equipment records against accidental or deliberate disposal or corruption. Reorganisation, downsizing, change of record system and change of company ownership are likely times for information to be ‘lost’.

- Periodic auditing of equipment to confirm that technical information in the Equipment Records is valid and up to date. Data on modifications should log whether the modification was completed and successful, or was abandoned.

(b) Production of equipment condition indicators

- Collating operating data, condition monitoring and inspection reports.

- Reporting containment failures with sufficient investigation to identify the causes and those related to equipment deterioration in a form that can identify trends.

- Analysing evidence indicative of deterioration.

- Reviewing whether the current monitoring / inspection regime is still appropriate.

- Giving particular attention to equipment that is approaching ‘end of life’ and which could be of concern for safety, or for the costs of replacement/major repair.

- For critical items at high hazard installations, this could be an annual report stating the known or predicted condition of all the key equipment.

(c) Reviewing comparative equipment performance

- Comparison of major plant items (individually) and minor plant items (by area or type) considering data on availability, maintenance, trips/failures.

- Trending of data by review of previous years (with corrections for changes in business or operating targets).

- Analysis of significance of changes.

(d) Setting of requirements for inspection and maintenance

- Setting maintenance and inspection policy, standards and targets.

- Agreeing qualification and experience levels (e.g. for fitters, welders etc.) and formal qualification to recognised standards for inspectors and NDT technicians.

(e) Verification of inspection and maintenance

- Assessing and ensuring competency and relevant training.

- Auditing for completion, timing, effectiveness, accuracy of reporting, cost effectiveness, and relevance to future activities.

- Determining future resource/subcontract policy to ensure cost-effectiveness.

- Periodic review of inspection and/or maintenance records to establish if approach, methods and frequency are still valid.

2.1.3 Plant Inspectors, Asset Managers/Technicians And Competent Persons

Where there is a need for equipment to be examined, there is a role for someone to specify and control the scope, nature, frequency and conduct of examinations consistent with the identified risks, failure modes and damage mechanisms. In many organisations this role carries the title of Plant Inspector, while in others, particularly those dealing with non-PSSR equipment, it may be Asset Manager or Asset Technician. For pressure systems, PSSR 2000 [A3] require a Competent Person, normally accredited to ISO/IEC 17020:2004 and affiliated to a corporate body, in this role. All those performing this role should have a suitable degree of independence from the operating functions of the company so as to be able to give an impartial assessment of the condition of equipment without conflict of interests.

Depending on the role, these activities may include the following:

- Verification of design and manufacturing integrity.
- Identification of any specific health and safety issues relating to the examinations.
- Providing guidance as to how the plant should be prepared for examination.
- Identification of the anticipated damage mechanisms.
- Establishing the scope and nature of the examination required, including the examination and testing of any protective devices.
- Determination of the date of the next examination and periodicity between them.
- Preparation and/or approval, and review/revision of written schemes of examination.
- Identification and assessment of the signs of damage.
- Sentencing of defects found during the examinations.
- Determination and approval of suitable repair procedures.
- Production of suitable report of any examination carried out.

Plant Inspectors, Asset Managers/Technicians, and Competent Persons are responsible for all aspects of plant examination, including inspection supplemented by NDT techniques[1]. There is an important distinction between this role and that of the NDT Technician: the NDT Technician is only responsible for applying the NDT technique specified in the procedure and reporting the NDT results.

[1] Note the definitions of ‘inspection’, ‘examination’ and ‘non-destructive testing’ given in the Glossary.

2.2 COMPANY CULTURE

2.2.1 Governance And Leadership

The standards of corporate governance and the behaviour of directors and senior managers can strongly affect the culture within a company or organisation, and consequently can influence the equipment it operates. A positive culture can be created through proper engagement, motivation and appreciation throughout the staff and supply chain. Directors and senior managers should consider the value of the following measures in creating conditions for a positive culture for the management of equipment. Case Studies 3 and 4 in Appendix 2 illustrate where poor company culture can lead to failures.

(a) Conducting a 'benchmark review'

This is a site visit to understand the plant and how it is operated (which should be a normal if irregular event, not a special occasion) and to show interest in the people and equipment within the plant. In making the visit, consider:

- The location of the site and its potential effect on the neighbours.
- The layout of the site and options for security, safe access, evacuation routes, vehicle access, parking, HGV segregation, etc.
- The condition of the buildings, infrastructures and services.
- The tidiness of the manufacturing areas, as a guide to operating culture.
- The variety of plant / equipment types on site. This will indicate if the improvement challenge is site-wide or localised (building on local good practice is often more effective than imposing new standards).

(b) Learning and analysis

Organisations that are able to analyse will learn by their successes, ("Why did it go well?") and failures ("What did not work properly and why?"), and make corrections and improvements. A blame culture is not generally a good way of gaining confidence and moving forward. An effective management sets high but achievable standards, realistic targets, and allows learning opportunities and time to do things differently.

Providing good opportunities for communication ensures that the operators, maintainers and supervisors can meet and freely feed back to management their concerns and ability to meet targets. Industry networks and associations can be very effective for sharing experience where competitive advantage is not a major issue. Time to read best practice guides and attend industry seminars can pay dividends.

(c) Empowerment

Senior managers and the management chain (slim though it may be on modern plants) exist to control, allocate and devolve certain responsibility. Day-to-day operations and checks should be the responsibility of operators, maintainers or supervisors who will, (if correctly selected, motivated and trained), thrive on having this responsibility. Senior managers should empower them to solve problems and make improvements within prescribed limits and following described practices.

(d) Problem tagging

In a good organisation, all members of staff should have the incentive, encouragement, opportunity and responsibility for identifying and solving problems within their area of working/competence. They may not, however, appreciate the legal, technical, practical and financial limitations on solving the problem. Therefore staff need support through a local management chain to ensure modifications are practical, safe and recorded.

Financial incentive systems can be used, but these should be approached with care – payments to individuals within a team can be divisive. Pride and influence in helping to solve a persistent problem can be the most powerful motivators.

Supervision of service contractors can be difficult; service contracts often provide a disincentive for the service engineer to be effective, by paying the minimum fixed fee then a charge (often including call-out) per visit. This encourages "quick fix" solutions without root cause investigation. Equally, local supervisors let the service engineer 'get on with it' without giving them a proper briefing or feedback on the problem they have come to solve, and explaining what is expected of them. This leads to poor service records with no date, no listed reason for the call-in, no clear indication of the problem, merely a list of parts replaced or cleaned.

2.2.2 Sharing Responsibility

All personnel share the responsibility for safe and reliable operation of the plant. Realistically, senior managers carry ultimate responsibility for systems and procedures. Operating and maintenance staff have responsibility for carrying out activities safely, and contractors for their own activities and the effect of their activities on others.

The responsibility for action is normally allocated to individuals or small teams. Managers are responsible for their team's compliance, not their individual actions. Good delegation gives individuals and teams a sense of ownership over what they have been allocated and the way of achieving the required goals.

(a) Reviewing processes

The support processes of operation, maintenance, inspection etc. are equally as important as the equipment; an unsafe item of equipment is often far more obvious to the experienced eye than an unsafe process. This is often because an inadequate system does not become obvious until it fails to prevent an incident. These processes (applicable to most management processes because they involve people) should be considered for registration, audit and review process.

This is particularly true of industries and locations with a high staff turnover, and thus poor 'corporate knowledge' at the shop floor level. Inexperienced staff may lack the knowledge to make judgements and provide feedback on working procedures.

(b) Decision making

It is good practice for Plant Managers to explain the background and reasons behind a significant piece of work to the person or team carrying out a task and to be open to comments and suggestions. The reasoning may influence the way the task is performed. For example, painting a safety critical item to prevent corrosion may assume a greater importance that painting for visual effect and a better result may be obtained. This is particularly true of tasks carried out by outside resources (e.g. service contractors), for many reasons, including:

- Better motivation if it is known why the task is being done and standards to achieve.
- They may know a better way of achieving the same result.
- The person carrying out the task could have a different view of the problem, thus contributing to the decision process and the solution.
- The specialist may understand the root cause of recurring problems and be able to suggest a permanent solution.

2.3 SETTING THE STRATEGY

2.3.1 Asset Management Policy Document

In complex installations, it is appropriate to have a defined written policy for management of the assets in terms of the equipment, and the feed and product inventory. This may provide identification of the risks from failures (both equipment and human), and an assessment of equipment condition and fitness-for-service. The asset management policy will be specific to the type of industry, plant location, and company objectives.

The policy document may define (but not list, except perhaps in Appendices) the assets concerned, with an overview of a means of managing, inspecting and maintaining each type of asset, and the design life of each plant or asset. As a generic document, it will deal pragmatically with risk (to safety, business, reputation, employment, and neighbours), recognising that all activities carry some risk and that the objective is to manage risk to the benefit of all. It may define the framework for plant outages and reliability targets in terms of production or availability.

2.3.2 Structural Integrity Management Plan

The Asset Management Policy Document may reference a Structural Integrity Management Plan (SIM Plan). This is a particularly important document for installations where there are high hazards and/or the inventory of equipment is large. The SIM Plan will normally set out the means and procedures by which structural integrity is assured to meet statutory and company requirements.

Typical elements referenced in a Structural Integrity Management Plan include:

- The original design assessment and design life.
- Operating limits and instructions.
- Maintenance policy document and equipment schedules.
- Inspection policy and schemes of examination.
- Fitness-for-service assessment and revalidation.
- Repairs, modifications and replacements procedures.
- On-line and periodic condition monitoring.
- Equipment retirement policy.

The plan should consider interactions between these elements and the relative strength and combination of the elements required for different categories of equipment.

2.3.3 Maintenance Policy

It is good practice to have a document that describes the maintenance policy for equipment. Manufacturers' recommendations for maintenance may be sound but can be over-protective. A risk-based approach is to identify the safety and production-critical equipment, and to analyse what may go wrong and set maintenance policy accordingly. Alternative approaches can be condition-based or reliability-centred.

Typical outcomes can range from 'no maintenance' through increasing levels of monitoring, inspection and maintenance. The resulting maintenance schedule is a balance between the impact of carrying out maintenance (cost, effort, downtime, risk of damage), and the impact of a failure (safety, cost, downtime).

When the maintenance policy and schedules have been defined, they should be explained to those involved in their implementation. It is useful to have a mechanism for feedback on performance through a system for recording and analysing equipment failures. This can then form the basis of an improved plan to balance maintenance cost and impact with the financial consequences of potential failures.

2.3.4 Examination, Inspection And NDT Policy

Examination, inspection and NDT are often an important part of managing equipment by providing information on the condition necessary to confirm that it remains within design limits or to assess fitness-for-service. For pressure and some other types of equipment, a periodic examination of inspections and other tests is a statutory requirement under PSSR 2000 and PUWER [A3, A6]. While other equipment and machinery may be exempt from regulations like PSSR 2000, the same principles of having appropriate examination apply.

Unnecessary inspection can be detrimental if it involves opening or disturbing equipment, or allowing in corrosive media. It can increase the risk of future failures (e.g. by damaging lagging, protective coatings and flanged joints). Incorrect application of NDT or inappropriate selection of inspection areas can produce a false sense of security by reporting no damage in the areas inspected, whereas damage may have occurred, or damage elsewhere may be missed. Inspection affects production and is usually labour-intensive, and can therefore be a significant cost (see Case Study 9).

For these reasons, inspection of equipment should always be well founded, and should be designed for the purpose of looking in particular locations for specific conditions, measurements, defects and flaws. Risk-based inspection (RBI), possibly based on a failure mode and effects analysis (FMEA), or at least specialist knowledge and experience, can be a good and recognised policy. Where the information required to support risk-based inspection is not available, and for certain high hazard low probability of failure equipment, a more general inspection may be used to establish or confirm changes to the base-line condition.

Schemes of examination should adapt to the age and condition of equipment and to the knowledge of its deterioration. For pressures systems over 250 bar-litres, PSSR 2000 requires the use of a Competent Person to draw up and/or certify as suitable a written scheme of examination. In general, the inspection policy needs to identify the approach to inspection planning and implementation, and the provision of NDT services.

New equipment, particularly on new processes or with new materials, may have no known history (e.g. of corrosion rate) and may need more frequent inspection. Early in life there may be great value in a sequence of measurements (e.g. thickness) taken at the same place, combined with a visual inspection taking a more general look in areas, which might be difficult to access or to clean. On equipment where experience shows little corrosion over 90% of the area, there is little point in continuing detailed thickness checks over the whole surface once this is established.

Most inspection policies will include visual inspection of internal and/or external surfaces. It is appropriate to use NDT to complement visual inspection for the detection of flaws that may be invisible to the naked eye. NDT can confirm and quantify expected deterioration mechanisms, and, when used at an appropriate interval, provides a means for condition monitoring.

In order to provide a measure of defence-in-depth, the inspection and NDT policy may need to include elements that would recognise damage due to unforeseen mechanisms, i.e. speculative inspections. Even when a full RBI has been developed with sound knowledge of the process operation, limited speculative inspection may be used to confirm its assumptions.

2.3.5 Strategies For Managing Corrosion And Vibration

In many plants, corrosion and vibration are threats to integrity that are so well recognised that it makes sense to have specific strategies for managing them.

Repair and replacement of corroded parts can be a significant cost to all plants. The management of corrosion is a complex yet achievable objective, but which can produce savings in the long run. The details of the methods are outside the scope of this report, and involve understanding the materials involved, environment (inside and outside) as related to criticality of the process and the equipment. At its simplest level a corrosion strategy may be just a schedule for repainting; at its most complex it may involve the optimisation of process conditions and holistic plant economics. Specialist corrosion or materials engineers have helped many companies draw up a strategy, reduce repair and maintenance costs, and demonstrate compliance with legislative requirements.

Vibration has similar issues, but is usually (but not exclusively) associated with rotating machinery and high flows. It can normally be managed by application of a number of techniques. Drawing up an appropriate strategy to manage vibration has the same requirement as corrosion for appropriate specialist support to give cost effective advice. The benefits from reduced vibration include reduced power consumption, wear, noise, risk of cracking, operator fatigue and equipment failure rates.

The vibration mitigation strategy can include the assessment of locations at vibration risk (e.g. small bore connections), strain gauge monitoring, re-balancing of rotating machinery, improved supports and pipe-route redesign. Dirty or scaling duty, build-up of deposits, (which cause out-of-balance and wear, often of bearings), and rapid changes in load and/or the operating environment (e.g. wind) are common causes of failure. It may be worth monitoring vibration periodically, which is often done as a tour by a specialist or trained operator, using a hand-held monitor with a data logger. The results are then loaded onto a computer, trended, and non-conforming items identified.

Continuous vibration monitoring can be used as a process tool (e.g. to identify fouling on a centrifuge). When vibration levels rise slowly over a long period of time, it is very difficult to define the point at which equipment is definitely damaged and should be stopped. Alert levels (e.g. process wash, alert management, stop & isolate) should be defined by management and set into the instrumentation or monitoring alert equipment.

Vibration detected on equipment that does not normally vibrate (e.g. heat exchangers) is often a sign of problems and should be investigated promptly. Similarly, a complete lack of vibration on something that normally vibrates indicates a failure, but probably does not indicate a safety issue, unless it concerns failure of components such as a stirrer or agitator in a batch reactor. The strategy should identify and recommend action for these contingencies.

2.3.6 Strategies For Machinery

Control of the adverse effects of ageing of machines is an important element in integrity management, but there are other aspects that are equally important. First you need to ensure that the equipment is suitable for the purpose for which it is provided. This assessment is generally more complex for machines than for static equipment: machines generally have less tolerance to use in situations to which they are not suited.

The same basic damage mechanisms apply to machines as to static equipment, but, in general, machines fail more frequently. The integrity of machines should be managed with a greater emphasis on the application of appropriate maintenance that adequately controls the risk of loss of containment. Typical maintenance activities may include dismantling for inspection, replacement of worn or damaged or life-expired parts, adjustment and lubrication.

Each maintenance activity should be planned in advance to ensure that the required time and resources are available. On duties with hazardous fluids, maintenance frequency is normally time-based or condition-based. Some equipment may be run with no scheduled maintenance (e.g. pumps) on the basis of a risk-assessment. Potentially hazardous leaks from seals should be managed by suitable safety-critical containment alarms, or low hazard leaks spotted during routine inspection.

(a) Time-based

Time-based maintenance is appropriate if the rate of deterioration is both known and consistent. Time in this context can either be calendar time or time to reach a defined position such as operating hours or total throughput.

(b) Condition-based

On-line condition monitoring can either be continuous or periodic. Both are carried out with the equipment in operation. The former provides a real-time view of the measured parameters, but it is more costly to install and operate. The latter provides intermittent information and therefore has more chance of missing rapid deterioration. However, in general, deterioration due to normal ageing mechanisms is relatively slow, and periodic condition monitoring is suitable providing that the intervals are not excessive.

The condition monitoring techniques that are most commonly used for machines are vibration and oil sampling. Thickness testing and thermography are also useful tools. Performance measures such as flow, pressure, temperature and power draw are the most effective ways of detecting fouling or blockages.

2.3.7 Process Control

Degradation of equipment is usually strongly linked to the process operating conditions in terms of the environment, loads and duty. Process control is therefore an important part of the equipment management strategy. Its aims are to ensure that equipment operates within its safe operating limits, while optimizing performance and minimising degradation, and it is a key instrument to prolonging equipment life.

Process conditions are often changed over the life of a plant, maybe as a result of changes in product, process or capacity. There may also be changes in conditions at times of shutdown, start-up, cleaning/decontamination. It is important to recognise and review the impact of such changes, and good co-operation between operators, maintenance and materials engineers is a significant part of process control.

In many cases during fitness-for-service assessment where damage has been detected, it has become clear that changes in operation increased degradation rates or introduced mechanisms that were not considered at design. Small changes that may not have been significant, as individual steps (e.g. small temperature changes, modified flush systems) became important over extended operation. It is often difficult to predict the impact of process change over an extended period, and where there is doubt increased monitoring and/or inspection is appropriate.

2.3.8 Role Of Insurance

As part of their business asset management strategy, organisations will often protect their assets and liabilities through the application of insurance. Typically an engineering insurance package for a piece of industrial equipment would include such cover defined losses as a result of ‘Sudden and Unforeseen Damage’ which would include breakdown, explosion and collapse of the insured property. These terms are usually defined as follows.

- Breakdown is defined as “the actual breaking, distortion or burning out of any part of the insured property, while in use, arising from mechanical or electrical defects causing sudden stoppage which necessitates repair or replacement before it can resume normal working”.
- Explosion is defined as “the sudden and violent rendering of the pressure plant, by force of internal fluid pressure causing bodily displacement of any part of the pressure plant together with forcible ejection of the contents”.
- Collapse is defined as “the sudden and dangerous distortion of any part of the pressure plant caused by crushing stress by force of steam or other fluid pressure”.

For any damage to equipment insured in this way, the amount payable is normally calculated on the basis of reinstatement of the insured property or other property destroyed or damaged. Reinstatement is defined in two ways:

- Where the insured property is destroyed “its replacement by similar plant of a condition equal to, but not better than, its condition when new”.
- Where the insured property is damaged “the repair of the damaged portion to a condition substantially the same as, but not better or more extensive, than its condition when new”.

A typical insurance policy of this type would not normally cover:

- The agreed excess amount
- Loss or damage by fire or theft etc
- The cost of maintenance or rectification of faulty workmanship
- The cost of rectification of :
  a) wear and tear, erosion, corrosion or other deterioration caused by, or naturally resulting from, ordinary work use or exposure
  b) gradually developing flaws or fractures which do not necessitate immediate stoppage
- Consequential losses
- Psychological impact of a vessel failure on both employees and customers and the loss of stakeholder confidence.

Insurance policies do not generally cover the repair and rectification of damage due to progressive deterioration. Where damage leads to sudden breakdown, such as a leak or more catastrophic failure, the insurance indemnity may depend on whether the damage was sudden and unforeseen, or naturally resulting from ordinary work use, and the way in which the equipment was being managed.

It is a normal condition of insurance policies that the insured shall take all reasonable precautions to safeguard the insured property against loss or damage. They shall maintain it in an efficient condition and take all reasonable steps to ensure that all Government and other regulations relating to the operation and use of the insured property are observed. Under these circumstances, most ageing mechanisms arising naturally from ordinary work use and exposure should be foreseeable; the courts are unlikely to accept the argument of sudden and unforeseen breakdown and accept insurance claims on this basis.

Whatever the circumstances, insurance cannot normally provide protection against liabilities when there is prosecution and conviction under health and safety law.

2.4 SYSTEMS FOR KNOWLEDGE MANAGEMENT AND RETENTION

2.4.1 Asset Registers

In order to track the existence and whereabouts of equipment at complex plants, it is helpful to maintain an asset register. This need not be a vastly detailed document, but a summary list of equipment items with a few key details (e.g. location, function, duty, number of items, remaining life, financial value, decommissioning date) held and regularly updated at site and plant level. Examples have been seen of companies paying to maintain and inspect equipment that is no longer in service, or even on site.

2.4.2 Equipment Record System And Maintenance Log

An equipment record system and a maintenance log containing information specific to each item of equipment is essential. In a modern plant these may well be computerised, or a combination of paper and electronic records. It is important to consider the security of the records against fire/accidental loss and to have a back-up system if appropriate.

Paper records have the advantage of being easy to browse, and to spread out on a table for discussion (perhaps out of hours, when the computers may be locked up). Records clearly filed by plant, section, equipment, date, purpose (inspection, spares, repair procedure, etc.) are more easily managed. Many computerised records systems are now available, often with scheduling capability and with a link to the asset register.

The record system should contain full details about the equipment. Design and manufacturing information should include design drawings, material mill and test certificates, welding and NDT specifications and reports, installation and commissioning tests, and quality assurance documents. Ideally, it should contain the operating instructions, and the duty and service history, which need to be regularly updated. It needs to include a record of maintenance, replacement parts, and inspection reports. Repairs and modifications also need to be recorded. These latter items may be held in a maintenance log separate from the equipment records.

If computerised, it should be possible to view all the maintenance actions for a whole plant section or single item of equipment. This helps to identify costs, problem areas, and recurrent problems (worthy of investigation by Root Cause Analysis etc.). The way data is recorded and accessed will vary for differing types of plant and one method will not be appropriate in all cases. The objective is to record data in such way as to differentiate between 20 new seals on one pump, and 20 new seals over several pumps.

A maintenance log need not be onerous or exhaustive. A brief statement of actions is normally all that is needed. Records should be in date order, accessible, and difficult to erase or remove without good reason (for this reason a loose-leaf folder is unsuitable). Fine detail (e.g. reports, parts lists, invoices) can go in the equipment record system.

2.4.3 Dealing With Backlogs Of Maintenance And Postponement Of Inspection

All process equipment will generate maintenance actions as it ages (e.g. painting, small leak repair, bolt tightening). These actions will be reported as requiring attention, but not all of them will be of equal importance. It can be difficult to monitor and progress all actions (particularly small items) in a busy working environment, and backlogs commonly arise.
Possible reasons for backlogs include:

- Longer intervals between shutdowns limits opportunity for maintenance.
- Less people available, maybe due to downsizing.
- A computerised maintenance system does not “forget” non-essential jobs, as may have been the case in a manual system.
- Open access to authors to input work requests.

The number and length of time overdue of maintenance actions may be a good indication of the level of management control. In the first instance, it is valuable to have an understanding of the reasons for these actions being generated as a mechanism for preventing failure and improving work processes and equipment effectiveness. There is a need to have an understanding of the frequency and effect of past maintenance and repairs to help set priorities. This will allow a focus on the actions that most contribute to sustaining equipment integrity.

The methods used by companies to manage maintenance actions are varied, but are generally based on a number of simple principles. These may be applied in any organisation to a degree that is appropriate to the inherent hazards and complexity of the equipment. These methods are being developed further in European collaborative projects, such as RIMAP (Risk Based Inspection and Maintenance Practices).

A first step is to evaluate the severity of the damage found or the potential damage being addressed by the maintenance action and to categorise its importance. For example, using a numeric scale, a small paint defect could be 1 while a hazardous leak could be 5. An appropriate timescale for action can then be set for different types of damage, from immediate to 6 or 12 months to longer term. It is also important to consider solutions that prevent recurrence rather than simple “fixes”.

In the process of prioritisation, it is suggested that the consequences of further degradation or suffering a failure are taken into account. The impact on other items of equipment needs to be considered. (A common example is small water leak that runs onto associated equipment and results in corrosion. This can be severe if it enters insulation or runs under a tank).

When the work is assigned there should be a periodic review of maintenance work-lists and set targets for work outstanding. This will reflect the changes that may occur in the requirements (e.g. priority or other activities / opportunities for completion). The work that is recorded in the maintenance system should have defined authorisation levels, for empowerment of individuals to edit, delete or authorise the tasks. Control over maintenance backlogs can be regained by a combination of appropriate rescheduling, increasing and focussing resource and management.

For non-pressure equipment there needs to be an internal management system for postponing inspection or repair schedules that must recognise the requirements of the relevant regulations (COMAH, IPPC, PUWER etc). For pressure systems under PSSR, there are legal requirements controlling the postponement of examinations and repairs, as specified by the Competent Person. With an appropriate technically justified case, postponement is a valuable method of managing work schedules

2.4.4 Computerised Systems

Control is required over the input of data and it is often best to get a dedicated person to do this, or restrict input access. The computer system should be able to log who inputs or edits safety or business critical data, and retain pre-change data until the change is validated. Any widely accessible computer system tends to collect corruptions of data. Appointing an owner who is responsible for policing the quality and quantity of data on the system is a good idea. Open read-only access (to non-sensitive data) is preferred so information can be made widely available. These measures can ensure that data is input in a thorough and consistent way, and that the data is structured to allow easy retrieval of information by a non-specialist.

Information from these sources is of most value where it gives a coherent description of the equipment in service. This allows trends and patterns associated with the equipment to be identified. Beware of having too much reliance on computer generated data if this prevents and inhibits proactive management.

It has been noted that the agreement to replace a maintenance log is often managed as a commercial activity and the value of history or description fields in databases is not recognised. Where these factors do not align within the new system, it is often viewed as an additional (unnecessary) expense to make the transfer. The loss of the valuable technical history may equate to several times the 'transfer savings'. If the link between a location, item serial number and the history record is broken or corrupted because of a badly planned transfer to a new computer system, the information becomes useless. Worse, the problem may not be recognised until it is too late or too expensive to recover. This may also happen as a result of movements of 'common items' for several locations. These should also be recorded.

The original system set up under a particular management system may not be applicable today. When the system is updated or replaced, data can be lost or corrupted. Valuable history data may be too expensive to convert into a new format. Data backup may be poor, with the potential to lose large amounts of irreplaceable data. The system in place should match today's needs while giving secure access (e.g. via CD or computer server) to a store of relevant historical data, particularly equipment drawings and inspection data.

2.4.5 Management Of Changes In Duty, Modifications, Repairs And Ownership

(a) Inventory control and changes in duty

As each piece of equipment is utilised, it is useful to record regularly on the maintenance log the duty and time of service, and when equipment is removed from service for maintenance and examination. Some of this information may also need to be included in the Equipment Records and Asset Register. This will assist with maintenance and integrity management. It is particularly important where equipment duty, service or conditions are changed or vary over time. The information will be useful in determining potential deterioration mechanisms, remanent life, and in knowing where the equipment is available. When equipment is returned to stock without replacement, there will be a progressive reduction in the equipment available, and local variations in condition will occur as time progresses.

(b) Modifications and repairs

When a piece of equipment is modified, there should always be a record of the changes made within the equipment record system. This is frequently well defined for pressure equipment, but may be overlooked or limited for other items. It is recommended that design changes made to equipment are transferred from the maintenance system as part of on-going repair and maintenance procedure. Case Study 14 is an example of difficulties that resulted when modifications were not recorded.

There is a need for proper specifications of repairs and a record of changes in the equipment as a result of repairs. There are many cases where control of repair is not well specified, particularly for non-pressure equipment (see Case Study 13). During maintenance, equipment is often removed and replaced, for return to stores for 'assessment and repair'. After a shutdown, the repair is simply described as 'strip and inspect' or 'refurbish to original'. This leaves a great deal of potential for work to be undertaken without due consideration of the duty and fitness-for-service. Case Study 12 illustrates this point.

(c) Changes in Ownership

The most radical impact on Knowledge Management may come when a company changes hands and the new owner replaces the entire maintenance department or decides to impose a new 'company standard' computer system.

2.4.6 Control And Instrumentation Systems

Modern control systems evolve at a faster rate than the hardware that they support. Thus a site with several plants may have several generations of control system, some of which may be retro-fits. Each system requires appropriate software, spares and programming skills. It may be quite difficult for a technician to work on different systems over a short time span without making mistakes. Each system should have a Change Control and Recording system.

Modern automation systems provide opportunities for data recording and trending of performance. These are valuable tools for assessing equipment. However, as instrumentation ages, it is more likely to give inaccurate or false data, due either to deterioration of measuring elements, or errors in set-up and calibration. Matching replacement parts may not be available, leading to re-use of substandard parts. Trending from older instrumentation may be suspect.

2.4.7 Planning For Process Events

It is helpful to have a system in which credible process events (e.g. pressure/temperature transients, contamination, trips etc.) that can have an impact on condition of the equipment are identified in advance, and to have a planned response. The effects (beneficial or detrimental) on operations and plant integrity of some maintenance actions (e.g. filter changes, cleans, grade changes, maintenance campaigns, changes to materials etc.) can also be considered in the same way. Good knowledge in these areas is often of considerable benefit to the business, and can justify the work required to set up and maintain the information in a formal system.

2.4.8 Failure Investigation, Root Cause Analysis And Feedback

There is considerable value in understanding the root causes of failure as a means of preventing future problems. The causes are almost always a combination of factors relating to the design, operation, maintenance and environment in which the item is working. In order to have an effective improvement process, which can eliminate or reduce failures, a process of root cause analysis is recommended to analyse and identify the reasons for failure and suggest measures that may prevent repetition. A system is required to feedback the results of a failure investigation to those who need to act on it.

2.4.9 Obsolescence Of Equipment

Contingency planning can save time when obsolete equipment needs to be repaired or replaced. Some manufacturing processes are simply not used any more, and there are frequently great difficulties with defining how to repair such an item. There may be no relevant modern design code, although the original code of construction may provide some guidance. The materials and geometry of older equipment may be completely unsuitable for welding, and the general deterioration of the equipment may increase the difficulties in making a repair. Inspection of welded repairs to older steels using methods such as ultrasonic testing may be difficult. Identifying where specialist advice or services can be obtained in advance can save time later.

An alternative solution may be a new unit to replace the function of the original, or an evaluation of the requirements to see if the function is still needed. In a process plant there are always a number of items of equipment, which are capable of performing a number of different duties in a plant. Typical examples are motors, pumps, valves or heat exchangers. The suitability of replacement equipment for a different application should always be assessed and recorded according to an appropriate procedure.

2.5 HUMAN FACTORS

2.5.1 Competencies Required

Managing equipment requires a range of competencies. Competence is both having and demonstrating the necessary knowledge, skills and experience to do a specific task within a particular context. Employers need to have sufficient knowledge to appreciate and employ the range of competencies required, and to maintain adequate control. Depending on the size of organisation and the type of equipment, the key competencies may be contained in-house, or accessed from sub-contractors and consultants.

The key competencies required to manage equipment containing hazardous and/or pressurised fluids include the following:

- Education and training in technical and mechanical engineering.
- Understanding of the relevant regulatory requirements and any approved code of practice and guidance for the equipment (See Section 1.6)
- Knowledge of design and construction codes and practices.
- Familiarity with the equipment concerned, together with the detail of the design and materials of construction, and the operation and maintenance requirements.
- Understanding of the metallurgical issues for the construction materials and the effect of environment so as to predict and/or prevent potential damage mechanisms.
- The necessary skills for operating and caring for the equipment.
- The knowledge and ability to plan inspection and maintenance to ensure safety.
- Experience of plant inspection, inspection techniques and NDT, and knowledge of their applications and limitations.
- The knowledge and ability to undertake routine maintenance tasks and to know when to refer to specialist contractors.
- Experience of welding, both practical skills and welding engineering.
- An appreciation of fitness-for-service assessment.
- The management skills for organising and ensuring necessary actions take place.
- Teamwork skills and understanding the roles of others.
- The communications skills to ensure that everybody knows what is happening.

The team of managers, supervisors and technicians that is responsible for the equipment must have these competencies and be organised in a way that utilises them in the roles they undertake. In many situations, the Competent Person, as required by the Pressure Systems Safety Regulations, will have many of the key competencies. Duty Holders should not rely solely on the Competent Person, but should take an active part in bearing responsibility through staff employed or contracted to their own organisations. In a non-regulatory sense, the Responsible Person is someone with the necessary authority and competence to be responsible for containment equipment, as covered by this report.

It is now common good practice for organisations to define the responsibilities of the different roles within an organisational structure. This leads to a statement of the competencies required for particular jobs and roles at all levels of responsibility, from technicians to managers. Certification to ISO quality standards of organisations operating hazardous equipment is now expected.

Pressure systems and chemical containment engineering require a range of competencies from the technical to the graduate professional. Ensuring the right blend of practical experience and engineering know-how is the key to successful management. Creating an underlying Key Competencies List for both Technicians and Managers focuses the mind on whether to train-up or buy-in what is needed.

2.5.2 Supply Issues

The skills and experience that are relied upon for the management of ageing equipment are becoming increasingly scarce in the workforce. There is no longer a steady supply of boiler engineers and other skilled workers from industries such as coal mining, shipyards and merchant shipping. New graduates entering in engineering industry can also be scarce, and those that do lack the necessary experience and continuity.

There can be a wide gap in age and experience between established experienced staff and their newly recruited colleagues. A lifetime's knowledge that has been built up by one person can be easily lost upon retirement. It is therefore necessary for you to consider how to retain corporate memory and skills about key equipment.

2.5.3 Transfer Of Experience – Succession planning

A wise organisation plans for the transfer of skills and knowledge to allow for staff development and turnover. Specific recruitment and training strategies may needed to develop these skills from less experienced staff. At other times, the skills and knowledge gap can be filled by hiring appropriate people or from subcontractors.

Succession planning is particularly important; the in-house knowledge upon which integrity management relies may have to be transferred several times. This just reinforces the requirement to identify what skills and competencies are needed, and arrange training – it is unreasonable to expect to recruit someone with exactly the profile and experience you need (unless you are prepared to pay highly for it).

2.5.4 Managing Established Workforces

Concerns over the supply of technical staff are reduced if the industry culture is for low staff turnover. An established workforce is often as effective as a younger one, having more experience, team commitment and stability. Management that reinforces these attributes will benefit and gain a return. Maintaining the team atmosphere and minimising change, giving employees the assurance that they will be looked after in retirement or when the equipment is decommissioned will engender continuing loyalty.

2.5.5 Specified Competencies

There may be a need, particularly where the maintenance of high-hazard equipment is outsourced, for a formal means of defining and controlling the skills of contract personnel. These require the contractor to buy into a system of training and validation, such that only appropriate personnel work on specified plant.

2.5.6 Technical Support For Inspection And Maintenance

A larger knowledge pool is required to help deal with question like "is this an age-related problem?" and "what do other people with this kit do that works?" The vendor may no longer exist, or have the skills to support older plant. In these circumstances it may be necessary to get advice from a specialist consultant.

2.5.7 Training, Competency And Certification Of Skilled Personnel (Including NDT And Welding)

A good training policy will have many sources of continuing professional development. Some will involve mentoring and on-the-job coaching and changes. Other sources include formal training courses, seminars and workshops.

Significant experience and professional development can be passed on by giving new and less experienced staff the chance to work with, and learn from, the more experienced colleagues. More experienced staff need to value the development of younger colleagues, who in turn need to appreciate that they have a lot yet to learn that has not been taught in college or university.

Mentoring can and should be very valuable, but there is also benefit in learning the correct approach while away from work pressures. Training courses and team workshops need to be part of an active company, since they may not occur organically. Where new, infrequent or complex maintenance tasks are involved, learning, re-learning or practice under classroom conditions are encouraged before the job is done.

Of particular relevance for ageing equipment are the formal requirements for the training and certification of inspection and NDT and welding personnel.

(a) Inspectors and NDT personnel

Carrying out an inspection to identify damage requires the engagement of competent inspection and NDT personnel. Both the plant inspector, who has a general responsibility for examination and the specification of individual inspections, and the NDT operative, who has skill in one or more NDT techniques, have a role to play. A competent individual will have an appropriate educational background and the required level of training and experience and, in the case of the NDT operative, someone who holds appropriate certification at the right level.

For plant inspectors or engineer surveyors engaged as Competent Persons in the inspection of pressure systems under the PSSR 2000 regulations, there is Approved Code of Practice. The attributes required for the individual and specialist services and the organisation depend on the size and complexity of the system. They range from individuals having adequate knowledge and experience with reasonable support in the case of minor systems, to having at least one senior engineer of Chartered Engineer status in each relevant discipline backed by a full range of services for major systems. UKAS[2] accreditation to ISO/IEC 17020:2004 [F12] is an indication of the competence of an inspection department, organisation or self employed person. It is appropriate to apply similar principles for inspectors of non-PSSR equipment.

Commercial courses for Plant Inspectors are available, although formal personal certification is not established. It is important, therefore, that the employers of these individuals, often insurance companies/inspection bodies, operate an in-house system of competency assessment in line with ISO 9000 requirements and industry best practice.

Third party certification schemes for NDT operatives that comply with BS EN 473 are available. These include the Personnel Certification in NDT (PCN) scheme (provided by the British Institute of NDT) and the Certification Scheme for Welding and Inspection Personnel (CSWIP) (provided by The Welding Institute). Certification is available, usually at three levels[3], in all the main NDT techniques including some of the more specialist techniques such as TOFD and phased array. Visual examination is covered under PCN and in courses for Plant Inspectors.

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[2] The UK Accreditation Service, an agency of the Department of Trade and Industry.

[3] Level 1 – supervised practitioner; Level 2 – practitioner; Level 3 – trainer/supervisor.

For companies employing their own NDT personnel, second party certification, for specific inspections, could be preferred. This form of certification is usually administered in accordance with the American Society for NDT (ASNT) recommended practice No. SNT-TC-1A [F13]. This specifies experience, training and examination requirements for certification, which the company carries out. Further guidance is available from EEMUA regarding competency requirements for inspection personnel [F6].

This focus on personnel competency is very necessary. The inspector/operative are the most influential part of the inspection system (the combination of procedure, equipment and personnel) determining how successful (or reliable) the inspection will be in meeting its planned objectives. An ineffective inspection does not provide assurance (see Case Study 9).

Even with the engagement of competent inspector and NDT personnel, operational factors can significantly affect human performance and impact inspection reliability. These factors include the adverse effects on performance of inspection where:

- Access to the component is poor or the level of working is uncomfortable.
- The external environment is 'hostile' (e.g. due to high/low temperature, noise, poor lighting, fumes, confined space, wet, radioactivity).
- There is time or management pressure.

Guidance is available from HSE in the form of a series of NDT Best and Recommended Practice Documents [G2], which address some of the human factor issues and recommend ways in which these issues can be mitigated. Extensive studies have been made into the affects that human factors have on inspection performance. Relevant publications provide further information.

(b) Welding personnel

Formal training is available for all levels of personnel involved when equipment is welded. The importance of good welder training is illustrated in Case Study 6 in Appendix 2. Increasingly, the European Welding Federation (EWF) Diploma qualifications are being sought for demonstrating competence in Welding Engineering to an appropriate level. The diploma can be taken at one of three levels: Specialist, Technologist or Engineer depending on the level of responsibility.

The diploma course covers the knowledge required to write appropriate welding procedures and to plan and manage welded repairs, as well as explaining the different welding processes, the issues associated with welding different alloys, and design and fabrication of welded structures. Practical welder and welding operator training is also important and is carried out for a number of reasons, including:

- To develop a new weld procedure and approval.
- To obtain welder approval to nationally and internationally recognised standards.
- To demonstrate the practical competence of welders.
- For improved weld quality with a minimum level of workmanship defects, reduced over-welding, and less distortion.
- For multi-skilling, so that an individual welder can handle a greater variety of work.
- For compliance with legislation, e.g. Pressure Equipment Directive (PED).
- To promote the company's (or welders') credibility.
- To achieve increased output from individual welders.

Welders with an aptitude for organisation or management may be suitable for the role of welding foreman/supervisor or welding inspectors. These tasks require further qualification such as that available through the CSWIP scheme (Certification Scheme for Welding and Inspection Personnel). This scheme provides a mark of competence for a wide range of people engaged in welding and/or inspection related jobs in building, operating, inspecting and repairing high integrity welded plant.

Welding high integrity equipment should be undertaken according to written welding procedures that are qualified to standards such as BS EN 15614:2004 (which has superseded BE EN 288) [B7], or ASME IX [B3]. BS EN 15614 uses methods such as mechanical testing of test welds to demonstrate the quality and approval of the procedure. The welders can also be qualified on the basis of such test welds, using the equivalent welder qualification standard such as BS EN 287-1:2004 [B8].

2.5.8 Demonstration And Recognition Of Competency

Competencies may be demonstrated by proven experience or by having suitable technical qualifications, dependent on the level appropriate for technicians, supervisors and managers. Certification is important. Many companies offer training courses appropriate to the management of pressure systems, tanks and related plant. Other sources of formal training are offered by accreditation institutions. Skills that people have should be recognised and documented, for example, by ‘Skills Passports’.

Many contracting organisations issue their staff with Skills Passports confirming training, competencies, and practical experience. These are useful when they enable the purchaser of services to have greater confidence in the abilities of the people employed. These are of more limited value if they only apply to a few employers / sites, or if there is doubt about the independence of the accreditation.

People (whether staff or contract) will only develop and retain specialist skills if they receive some appropriate individual recognition for their efforts. Combinations of financial reward and continuous, congenial work may provide the incentive. Extending the knowledge and skills of the workforce is simply good management.

2.5.9 Management Of Communication, Maintenance, Inspection And Technology

(a) Communications

Teamwork and communication are important for the efficient and effective management of equipment. A culture where it is easy to ask questions and point out problems will probably suffer fewer ageing-related equipment failures that one with a fixed hierarchy and less communication. Management encouragement for staff to learn beyond what is strictly necessary to fulfil their role will produce a more flexible and understanding organisation.

Face-to-face contact is always valuable, and sometimes irreplaceable in analysis of problems and in producing effective time-conscious solutions. Verbal descriptions of problems can be wildly misleading. On-line data, even if only at a summary level, can help to eliminate unsuitable lines of enquiry and identify potential solutions. Access to drawings, particularly if offsite specialist technical support engineers can also see them, gives a better chance of understanding the failure before dismantling the equipment. With ageing equipment, the vendor cannot necessarily be relied on for drawings or advice.

(b) Human Factors in Maintenance

Human error is always a concern within maintenance. Modern equipment designs have evolved to give supposedly easier, cheaper, and quicker maintenance, and certainly some design errors have been corrected and make far less demand on brute force and fitting skills. Be aware that equipment which has been dismantled a number of times has the risk that maintenance errors may have been compounded to exceed original tolerances or allowances.

Two HSE Research Reports give some guidance in these areas. These are RR 213 'Human Factors Guidance Appropriate Management Strategies for Safety in the Offshore Oil and Gas Industry' by Vectra Group Ltd 2004 [E2], and RR 237 'Maintenance System Assessment: Guidance Document' by Poseidon Maritime UK Ltd 2004 [E1]. Guidance can also be obtained from HSE's publication on 'Improving Maintenance – A Guide to Reducing Human Error' [E3].

(c) Management of NDT service providers

It is increasingly common for plant owners/users to subcontract the management and site execution of NDT activities to an NDT service provider. While this approach can have advantages, problems can occur if the NDT provider is not properly instructed (see Case Studies 5 and 9). Good management of NDT service providers by the equipment owner/user and, in the case of Pressure Systems), the Competent Person, lays the foundations for effective NDT.

Larger companies often have an in-house inspection team or individual inspector who can plan examinations and specify and monitor the work of the NDT service provider. Where there is no one suitably qualified for this role in-house, companies can use independent inspection consultants or inspectors from Competent Person organisations. It is beneficial to retain a degree of independence from the NDT service provider, but to take their views into account. Issues could include whether optimum NDT technique has been selected, or whether a particular technique and procedure has been qualified for the application.

Those managing NDT service providers need to be suitably qualified and experienced to undertake the role for the equipment under scrutiny and the NDT techniques proposed. A formal NDT qualification may be required in some circumstances. Sufficient knowledge of the equipment is needed for the inspector to draw attention to geometric features, possible damage, and aspects of access and safety.

When selecting an NDT service provider, look for one who operates a quality management system to a recognised standard (e.g. ISO 9000), and who is a member of the Service Inspection Group of the British Institute of NDT. Prior experience of the type of equipment and the techniques proposed is an important attribute. Experience has shown that NDT contracts based on time and materials with a limited liability produce a more effective inspection than those based on fixed price. In either case a target time limit may be set, but bonuses for completion within time must be linked to adequate controls over quality.

(d) Dealing with advancing technology

You should be aware of some of the pitfalls relating to advancing technology. Modern manufacturing methods have generally reduced tolerances significantly. While metric and imperial tolerances are basically the same, there is a risk of a 'remembered' imperial tolerance being incorrectly converted into metric. The imperial trained user will not recognise that the measurement is nonsense.

Ageing equipment may be difficult to dismantle, e.g. due to corroded or distorted joints, lack of drawings, lack of special tools. There is no universal replacement for original asbestos jointing; judgement is required to select the best replacement, which may not give the same results as the original. Re-engineering may be required to recover damaged joint faces and fit modern gaskets. New skills and knowledge in the workforce may be required.

Equipment needing skills that are now rare or becoming obsolete presents another challenge. There may not be formal training available on ‘obsolete’ skills. Examples include the inspection and repair of riveted boilers. Where particular techniques (e.g. packing glands, working on cast iron pipe) are required in order to continue to operate ageing equipment, deliberate effort is needed to retain and maintain the capability to apply these archaic methods. These things cannot be outsourced, except perhaps to specialists. Beware the single expert tradesman – what do you do when they retire?

3 IDENTIFICATION OF AGEING

3.1 MANAGING EQUIPMENT LIFECYCLE

3.1.1 Degradation Rate And The Accumulation Of Damage

By its nature, industrial equipment containing hazardous and/or pressurised fluids is exposed to conditions of stress and environment that ultimately will degrade the material fabric from its initial state. Damage will accumulate until the equipment reaches a state in which it is judged to be no longer fit-for-service. Unless repaired or re-rated, the equipment may be said to have reached the end of its life. As damage accumulates, failure becomes increasingly probable, and if not withdrawn from service, failure of some kind will eventually occur.

The type of equipment and characteristics of duty can significantly influence the life. It is not unusual for machines with moving parts to degrade rapidly and to have very limited tolerance to damage and deviations from the design conditions in terms of human error or variations in process conditions. Static equipment, such as process vessels and pipes, tend to have much greater tolerance, and under benign conditions, can remain in-service for many years. In general, machines in the chemical process industries have proportionally more failures early in life than static equipment. There is, however, too much variation in the causes and rate of damage accumulation, to be specific, and the life of different items can vary markedly.

Even when new, or after repairs, equipment may already contain manufacturing and installation defects that can be the seed for an increased rate of degradation during service. Welding defects, crevices and poor fit-up and alignment of components are typical. Because items of equipment can be individually fabricated, often with manual welding processes, there can be distinct variations in quality between items of nominally the same construction. These variations are much reduced where there is good quality assurance and quality control during fabrication.

When equipment is new and first exposed to its service conditions, it may experience an initially greater rate of change than later in life. Bolted joints may leak and require tightening as seals and gaskets bed-in, valves and pumps may be stiff until wear ensures optimum running. As plant is brought on-line for the first time, there may be a greater risk of operating transients.

Typical measures of damage are the number and size of cracks, or the loss in wall thickness. Rates of degradation can be highly variable and non-linear depending on the degradation mechanism and the local conditions. While wall thickness loss due to corrosion may proceed at a constant rate (but not always), the number and size of creep and fatigue cracks and local corrosion tend to accelerate with time. There can, however, be circumstances where the rate of degradation slows or even stops. Corroding areas can build up a layer of oxide that inhibits further attack. Fatigue cracks can stop growing for a while if subjected to an overload.

The manner of operation, maintenance, inspection and repairs can strongly influence the rate of degradation. Invasive work can introduce contaminants into the system, and increase the rate of degradation, both temporarily and in the longer term. Appropriate inspection, maintenance and repairs of damaged areas can reduce both the amount and rate of damage, while unnecessary work has little gain.

Typically, accumulated damage and degradation rate rise with time, (Fig.3a), and hence the probability that an individual component will fail from this accumulated damage normally rises over time. However, this probability of failure can be altered by appropriate inspection, maintenance, and repair of damaged areas. The risk of failure then oscillates between the maximum and minimum operating risk levels, with the periodicity decreasing as maintenance, inspection and repair become more frequent later in life (Fig.3b). Fig.3c shows a model (bathtub) curve for the probability of failure from degradation for a large population of equipment rather than a single item. In these figures, the life is shown in Stages, which are explained in Section 3.1.3.

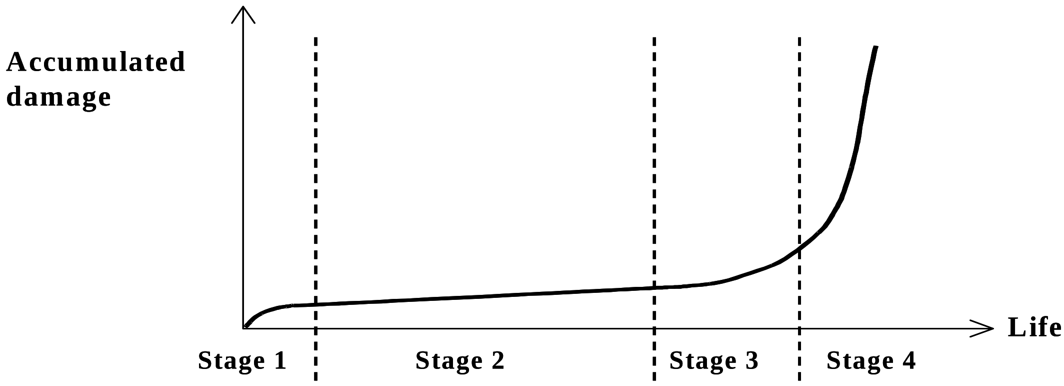

Figure 3a Variation of accumulated damage during equipment service

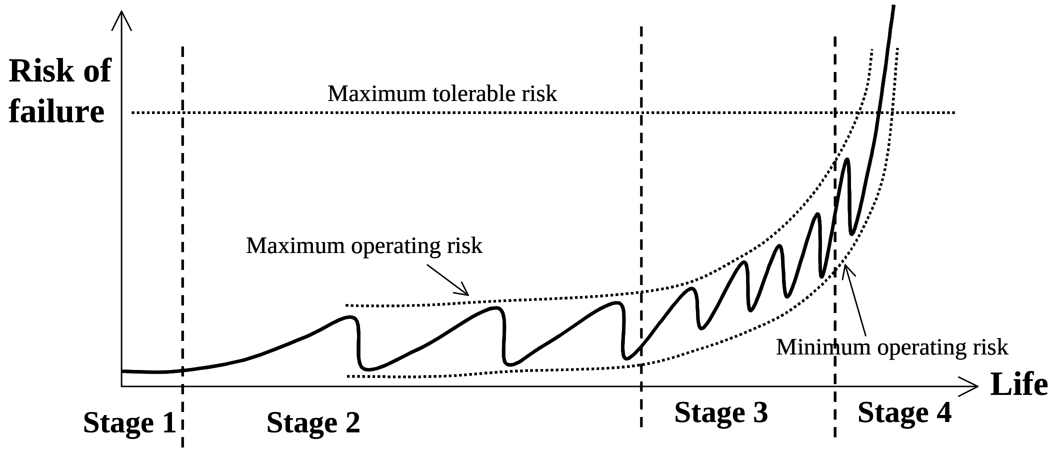

Figure 3b Effect of periodic maintenance, inspection and repair on the risk of failure for a piece of equipment. Each saw-tooth represents an inspection being carried out

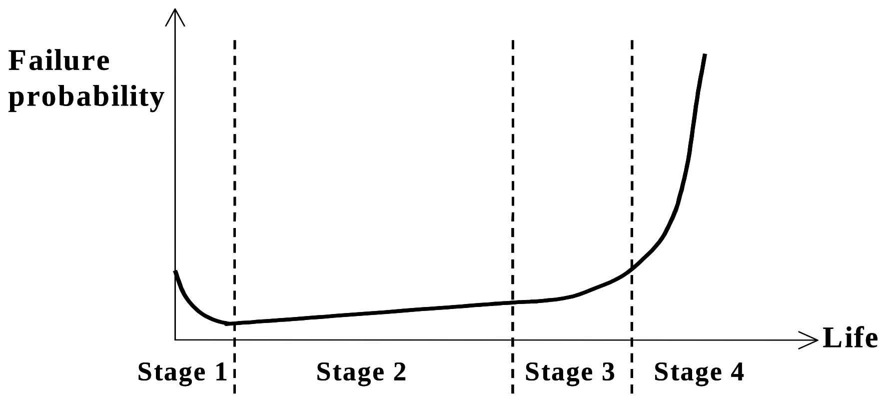

Figure 3c Model for the probability of failure of a population of equipment

3.1.2 Field Data

Published data of numbers of defects detected in equipment is scarce. In a survey for HSE [F11], SAFed recorded the total numbers of defects detected from inspections of pressure equipment of different types and ages over a period of about a year. Figure 4 shows the numbers of defects detected rising against the age range of the equipment at the time of inspection. A large number of defects were detected, particularly in older equipment. However, further insight cannot be drawn without knowing the amount of equipment in each age range and the number and extent of inspections carried out.

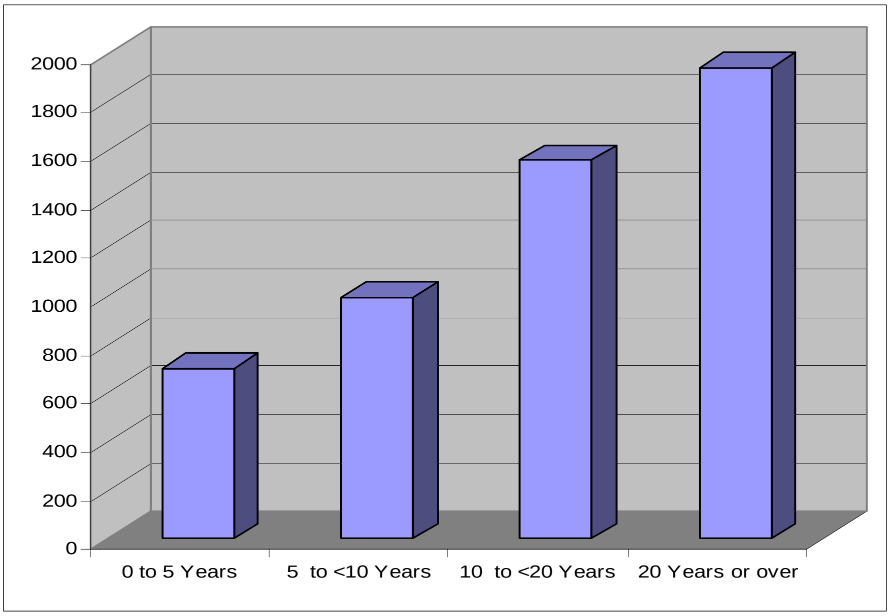

Figure 4a Defects detected by SAFed inspections of pressure vessels in 4 years

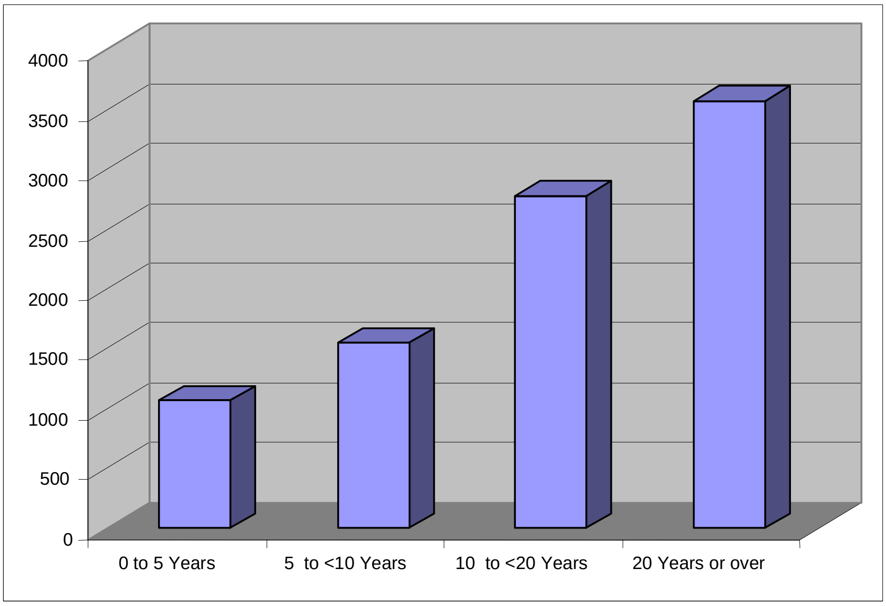

Figure 4b Defects detected by SAFed inspections of all equipment types in 4 years

3.1.3 The Four Stages Of Equipment Life

For the purposes of lifecycle management, it may be helpful to consider an item of equipment as having four Stages in its life, each with certain characteristics and having a different management, inspection and maintenance strategy. Following the discussion in Section 3.1.1, these Stages may be considered as:

- Stage 1: Post Commissioning ('Initial').
- Stage 2: Risk-Based ('Maturity').
- Stage 3: Deterministic ('Ageing').
- Stage 4: Monitored ('Terminal').

The four Stages relate to the amount of accumulated damage, the rate of degradation and the margins before fitness-for-service is compromised. These may correlate to the age of the equipment, and it would be normal for equipment to move progressively from Stage 1 to Stage 4 as it gets older, but this is not necessarily always the case. Some Stages may not apply to some types of equipment, and sometimes equipment can be moved back a Stage with appropriate justification. There are no fixed periods or clear demarcations between the Stages. It is matter of judgement from the particular circumstances at which Stage the equipment lies and the best management strategy.

The time that equipment may be considered to be in a particular Stage can vary markedly from one item to another depending on the operating environment and life history. The Stage within the lifecycle can be determined and controlled from finding out about the degradation mechanisms, undertaking assessment, monitoring, maintenance, repairs and refurbishment.

The four Stages of life are summarised in Table 1 and are described in the following pages. The approach to inspection for each Stage is discussed in Section 3.4.1.

Stage 1: Post Commissioning ('Initial')

As equipment is put into service there may be a relatively higher rate of damage accumulation and issues requiring attention. There are two main causes.

The first is where experiencing service conditions for the first time reveals an inherent weakness or fault in the design, materials or fabrication. Typical faults include incorrect dimensions, faulty material, welding procedures and fabrication defects that have not been identified from manufacturing NDT, or the effect of loads and environments that were not foreseen. Under these circumstances, rapid degradation of the equipment early in life is possible and it can progress quickly through the different Stages. Many of these issues can be eliminated with appropriate quality assurance and control.

The second cause of early life adjustments arises from bedding-in effects that the equipment may experience as it enters service. These can be as a result of large installation stresses or damage from mal-handling during installation. They can also be due to variations in service conditions as the equipment experiences 'shake-down' and loads redistribute themselves throughout the structure. Other non-critical symptoms of the 'Initial' Stage may be leaking valves, bolts or seals that are not fitted or bedded perfectly. Most of these problems can be managed through routine maintenance.

Stage 1 integrity issues can be identified and addressed at the first comprehensive examination. The timing of the first examination can be determined from a thorough assessment of the factors that might threaten integrity early in life. These factors include the stability of all process conditions, quality of construction and fabrication inspection. Where the process conditions are stable and a good fingerprint examination (prior to service) has been made, a risk assessment may be able to justify a longer period before the first examination than that recommended in industry guidance [F1, F2].

Stage 2: Risk-Based ('Maturity')

After the equipment has passed through the early-life problems of 'Post Commissioning', it enters the second Stage. The 'Maturity' Stage is when the equipment is predictable, reliable and is assumed to have a low and relatively stable rate of damage accumulation and few issues requiring attention. It is operating comfortably within its design limits. Examination and inspection, maintenance and NDT are generally to confirm the basis for these assumptions, and their scope and periodicity can be risk-based.

Stage 3: Deterministic ('Ageing')

By this Stage the equipment has accumulated some damage and the rate of degradation is increasing. Signs of damage and other indicators of ageing are starting to appear (see Section 3.3). In this Stage it becomes more important to determine quantitatively (hence 'deterministic') the extent and rate of damage and to make an estimate of remanent life. A more proactive approach to equipment management, inspection and NDT is required. Design margins may be eroded and the emphasis shifts towards fitness-for-service and remanent life assessment of specific damaged areas.

Lack of knowledge can be just as much a problem and can put equipment into Stage 3. Knowledge of the equipment's history may have been lost, perhaps as a result of the equipment being second-hand, or changes to the process for which the equipment is used, or from changes in personnel, record keeping and other human factors. It may now no longer be possible to predict the current condition or future service life of the equipment from design or risk-based considerations. Second hand equipment is assumed to be directly in Stage 3 unless there are sufficient historical evidence and records to demonstrate a lower risk.

Stage 4: Monitored ('Terminal')

As accumulated damage to equipment become increasingly severe, it becomes clear that the equipment will ultimately need to be repaired, refurbished, decommissioned or replaced. The rate of degradation has become increasing rapidly and is not easy to predict. In this final 'Terminal' Stage of the equipment's life, the main emphasis is on guaranteeing adequate safety between examinations while keeping the equipment in service as long as possible.

Stage 4 can be managed through making more use of on-line monitoring of the damaged areas, or by more frequent NDT to monitor the sizes of flaws until they reach the maximum tolerable size, or by repairing unacceptable flaws. A reduction of the severity of the duty, for example reducing the pressure rating of the equipment may be another option to maximise the usefulness before decommissioning. However, by Stage 4 no guarantees can be made about future service life beyond the next examination.

Table 1 Description of the four stages of progressive ageing

STAGE 1	**POST COMMISSIONING ('INITIAL')**	• Design and manufacturing faults • Installation issues (bolting, valves, leaks) • Commissioning issues (over/under filling) • Early life operating faults (training, trials) • Shake-down • Identification of potential ageing sites • First thorough examination (finger-print) • Reducing rate of problems
STAGE 2	**RISK-BASED ('MATURITY')**	• Operation well within design limits • Retained corporate knowledge of design/ manufacture • Ageing damage not yet significant; • Routine maintenance • Extended operating periods • Selected inspection, by risk analysis, to confirm expectation of slow degradation • Updated risk analysis from experience • Rate of damage low and predictable
STAGE 3	**DETERMINISTIC ('AGEING')**	• Design limits approaching • Evidence of active deterioration • Repairs, refits, modifications • Changes in process/use • Lack of full history/corporate memory • Changes in ownership; second hand plant • Quantitative NDT inspection to measure extent and rate of damage accumulation • FFS assessment required for life extension • Degradation rate increasing - less predictable
STAGE 4	**MONITORED ('TERMINAL')**	• Accelerating and accumulating damage • Beyond design limits and known operating experience • Approaching safe operating limits • Advanced inspection and FFS required to determine residual life • Decreasing intervals between inspections • Monitoring • Major repairs and refits replacement needed • End of life based on costs of repairs or replacement and wider economic factors

3.2 DAMAGE TYPES AND MECHANISMS

3.2.1 Categorisation

Damage due to degradation can be divided into that which directly changes the material of the equipment and that which may prevent the equipment or the flow of fluids from working properly. While the latter may not directly threaten the containment boundary, problems, such as vibration, scaling, or seizure, can affect the operation of the equipment in a way that eventually becomes a threat to integrity.

3.2.2 Types Of Material Damage

Damage to material can be categorised into four main types:

- Wall thinning.
- Stress-driven damage, cracking and fracture.
- Physical deformation.
- Metallurgical / environmental damage.

These are described below with examples. Some types of damage can result from several initiating mechanisms. Some initiating mechanisms can result in different types of damage depending on the circumstances. It is therefore difficult to separate the damage type from the mechanism that produces it and knowledge of both is required.

A compendium of some of the damage mechanisms may be found in API RP 571 [I2] and 'Macaw's Pipeline Defects' [I7]. Descriptions of damage mechanisms are also available in other publications.

Methods for the detection of these damage types using non-destructive testing are summarised in Table 5 and Appendix 4. Assessment methods for determining fitness-for-service of equipment with these types of damage are described in Section 4.2.

(a) **Wall thinning** may occur due to:

- *General or localised corrosion or corrosive pitting*. This chemical removal of surface material may occur by numerous mechanisms depending on the specific environment and conditions of fluid flow. Where corrosion causes intergranular attack, the surface layers may be weakened but still present. Where wall thinning due to corrosion is predictable, a corrosion allowance may be incorporated in the design wall thickness, based on a predicted corrosion rate.
- *Erosion, erosion-corrosion, scouring.* The action of particles in the fluid removing material from the surface.
- *Wear, abrasion, fretting.* Where two moving parts rub together.
- *Overgrinding* As a result of flaw removal for example.

For evaluation, wall thinning is categorised as general thinning, a locally thinned area or pitting.

(b) **Stress driven damage, cracking and fracture** includes:

- *Fatigue damage and cracking*. Fatigue results from cyclic stresses from, for example, varying pressure, vibration, resonance of small bore attachments, repeated differences in thermal expansion or thermal shocks. The rate of cracking may be increased under corrosive conditions.

- *Creep cavitation and creep crack growth* are damage from application of stress at high temperatures.
- *Stress corrosion cracking (SCC)* requires the combination of the presence of a stress (which can include welding residual stress), a susceptible material and a specific environment. It is generally characterised by a very fast crack propagation rate, and a branched type crack morphology, which can be intergranular or transgranular. SCC in different forms can occur in ferritic, duplex, and stainless steels and weldments. Environments that may cause SCC are specific to the material. Information on material/environment combinations that can cause SCC may be found in the NACE handbook [I1]
- *Stress influenced hydrogen cracking* can occur by a number of mechanisms where hydrogen is present in a material under the influence of an applied tensile stress or residual stress. This, in conjunction with the low ductility, can lead to fracture. Examples include fabrication hydrogen cracking and stress oriented hydrogen induced cracking (SOHIC).
- *Brittle fracture or cleavage*. Ferritic materials operated at low temperatures may be particularly susceptible unless materials qualified for low temperatures are used.
- *Ductile tearing* of pre-existing defects which can then result in fracture.

(c) **Physical deformation**

- *Dents and gouges* e.g. from impacts.
- *Buckling* e.g. collapse from compressive loading, vacuum or external pressure.
- *Yielding* e.g. from welding, overload or thermal shock, which can induce a permanent residual stress.

(d) **Metallurgical and environmental damage** (aside from SCC) involves a change to the metallurgy and properties of the material. It covers:

- *Hydrogen embrittlement.* Loss of ductility in steels and some other alloys due to the presence of atomic hydrogen, often as a result of hydrogen being absorbed by the metal from a suitable environment. This can cause stress corrosion cracking, disbonding of clad corrosion resistant alloy layers, and fabrication hydrogen cracks.
- *Temper embrittlement* of low alloy steels is caused by holding within, or cooling slowly through temperatures just below the transformation range, typically in the range of 450-475^{o}C.
- *Strain age embrittlement* of ferritic steels. Loss of ductility (and rise in strength) caused when a low carbon steel is metallurgically aged under sustained stress, time and temperature following plastic deformation (e.g. a dent). The degree of embrittlement also depends on the concentration of elements such as carbon and nitrogen in the steel.
- *Embrittlement* from other sources, such as sigma phase formation in some stainless steels.
- *Blistering/Hydrogen (Pressure) Induced Cracking (HIC/HPIC)* Dissolved atomic hydrogen in the steel recombines at inclusions and results in surface blistering or internal cracking.
- *Hydrogen attack.* The reaction of dissolved hydrogen with carbides in ferritic steels resulting in decarburisation and porosity. Can be avoided through correct steel selection.
- *Type IV cracking* is high temperature creep cracking that occurs over long times at regions of high stress, e.g. the outer edge of the visible heat affected zone (HAZ) in ferritic steel weldments or areas of local deformation. It has been detected in most creep-resistant low alloy ferritic steels, e.g. 1-1.25%CrMo, 2.25%CrMo, 9%CrMoVNb.

- *Reheat cracking* generally occurs in the weld fusion line in steels alloyed with combinations of Cr, Mo, V and B. In the welding process during reheating of the HAZ (e.g. generally during post weld heat treatment or subsequent welding), cracks form along weakened grain boundaries.
- *Flame impingement* can change the metallurgical microstructure of a material in the same way as heat treatment.
- *Ageing of polymers* due to exposure to ultraviolet radiation, high temperature or chemical attack.

3.2.3 Damage To Machines And Flowing Systems

Time dependent damage mechanisms in machines and flowing systems that could affect containment have their origins in corrosion, other chemical effects (e.g. precipitation, deposition, swelling), wear, erosion, fatigue, creep, seize-up and fouling. Some of these are calendar time related whereas others are more dependent on running hours. Some also directly lead to loss of containment whilst others may be the root cause of a consequential failure. Some illustrative examples are:

- Build up of solids on a fan impeller can cause fatigue failure and ejection of parts.
- Corrosion or fouling of turbine over-speed protection devices.
- Valve seizure (particularly important for pressure relief valves).
- Fouling of an oil cooler which causes lubrication failure that in turn causes bearing failure, resulting in shaft failure and ultimately, breach of containment.
- Blockage of heat exchanger tubing/pipes.
- Corrosion or fouling of pumps or fan impellers can reduce throughput and adversely affect the performance of associated equipment, e.g. a cooling system.
- Vibration of rotating equipment due to out of balance.

3.3 INDICATORS OF AGEING

3.3.1 Indicators And Risk Factors

An indicator of ageing is a sign or evidence that some damage has already or is about to occur. Indicators can be thought of as symptoms of ageing damage. Risk factors are conditions or circumstances that can promote or accelerate degradation, or a lack of control, but are not necessarily sufficient for ageing to occur. They can be specific scenarios, occurrences or events that can predict or suggest that deterioration could occur in the future.

Table 2a provides brief details of various indicators or symptoms of ageing that may be evident in equipment; while Table 2b provides brief details of various risk factors.

Table 2a Indicators or symptoms of ageing

Indicator	Details
Blistering or damage to surfaces	Paint blistering or other surface damage indicates that some degradation may be occurring.
Leakage	Leakage may be due to lack of maintenance (e.g. replacement of seals or gaskets) or it may indicate more serious damage such as a through-wall crack.
Breakdown and need for repair	Repeat breakdowns and need for repair suggests that the equipment has reached Stage 3 of its life (See 3.1.3 above). It is good practice to establish the underlying reasons for breakdowns and repairs.
Inspection results	Inspection results can indicate the actual equipment condition and any damage. Trends can be determined from repeat inspection data.
Reduction in plant efficiency	Reduction in efficiency, in pumping capability or heat up rates can be due to factors such as product fouling or scaling.
Lack of process stability	Excursions from the normal process operating envelope may mean that the equipment has deteriorated.
Product quality	Impurities in the product from plant materials can indicate corrosion or erosion. An on-going product quality review can detect variations in product quality.
Instrumentation	Lack of consistency in the behaviour of process instrumentation can suggest process instability and may indicate that the equipment has deteriorated. It could also indicate a fault with the instrumentation.
Experience of ageing of similar equipment	Unless active measures have been used to prevent ageing of similar equipment it will be likely that the same problems can occur again.
Poor condition of paint and surface coatings	Risk of corrosion. Also a risk factor which can demonstrate a lack of proper maintenance, and increases the risk of corrosion.
Repairs	May indicate that ageing problems are already occurring. Also a risk factor since if repairs have been needed during the life of the equipment, the integrity and necessity of the repair will indicate the potential for further problems.

Table 2b Risk factors for ageing

Risk factor	Details
Equipment age	The symptoms of ageing normally become more apparent with time, and older equipment may be expected to have more damage and deterioration than new. Age is not necessarily a risk factor. Older equipment that contained large design margins or has simply been well maintained may be still in an early Stage of life compared with newer equipment that has not been as well managed.
Equipment designed and manufactured to 'old' codes	Equipment designed and manufactured to superseded standards and codes, such as BS 1500, may be more susceptible to ageing than more modern equipment. Parent metal quality, welder and procedure approvals, Charpy requirements and dimensional tolerances may not have been as well controlled, or at least not to current standards.
Lack of low temperature justification	Equipment operated at low temperatures (generally below 0^{o}C) needs to be assessed against risk of brittle fracture, e.g. by using materials with specified low temperature impact values. Lack of low temperature justification is a risk factor for such equipment.
Outdated materials	The changes in steelmaking in the 1970s have resulted in much cleaner steels since then. Older steels can contain residuals (S and P) of 0.05%, whereas levels of 0.01% can now be obtained. The carbon level has also dropped over time as a result of modern microalloyed steels. This means that older steels have a higher tendency for cracking as a result of welding – particularly a consideration for repair welding older material.
Welding quality, welding defects and repairs	Poor quality of welding and joint design are key factors promoting the on-set of ageing damage. Welding has improved markedly during the last 40 years with better design, improved process control and quality standards. Modern welding consumables can also reduce the potential for hydrogen cracking of arc welds. More effective ultrasonic NDT methods have improved the ability to detect and size weld flaws.
Equipment without fatigue assessments	Fatigue analysis considerations were not a requirement for general pressure vessels designed to the early construction standards. Often a limit to the number of stress cycles was given, but no further assessment was possible. Experience has shown that equipment designed to early codes, such as BS 1500, BS 1515 and BS PD 5500 before 1996, can experience fatigue problems in service.
Design fatigue life/ corrosion allowance utilised	Once the design fatigue life or corrosion allowance is used up, a thorough inspection and fitness-for-service assessment is normally required to extend life.

Table 2b cont

Risk factor	Details
Re-occurring service problems – unplanned shutdowns	Any problem, no matter how small and insignificant, that continues to re-occur during service is an indication that conditions in the equipment are not optimised and may make it prone to degradation. Good inventory control is important for detecting these small but recurring faults.
Corrosive environments	A corrosive environment has the potential to cause corrosion to exposed surfaces if not properly protected. Attention should be paid to crevices and stagnant areas and to regions of composition differences, such as at welds. Additionally, some materials are susceptible to stress corrosion cracking in specific environments.
Predictable deterioration	It is important to monitor the extent of predictable deterioration (e.g. wall thinning) through review of inspection reports and service history to determine the rate of ageing of the equipment. Was the predictable deterioration accurately anticipated from design?
Change of service	If the operating conditions of equipment change then it can have an increased risk of ageing until service history or experience shows otherwise. Particularly for equipment purchased second-hand. See Section 4.4.
Failure of cathodic protection systems or lack of records	If a CP system has failed, or records not adequately maintained, there is an increased risk of corrosion occurring.
External hazards, mechanical, thermal or fire damage	Surface impacts due to collision from moving equipment can result in small defects, which can act as initiators for mechanisms such as fatigue or corrosion. Thermal and fire damage can alter the metallurgy of a material so that it can subsequently lose strength, toughness or corrosion resistance.
Poor condition of paint and surface coatings	See Table 2a
Repairs	See Table 2a

It is important to identify indicators and risk factors early so that a more detailed investigation of ageing and remaining life can be made before a dangerous situation develops (see Case Study 7). The presence of a combination of several indicators and risk factors may indicate a higher risk of deterioration than the presence of each in isolation. These different indicators and risk factors can help you to determine the likelihood that your equipment is suffering, or about to suffer, ageing damage and/or detect its occurrence.

3.3.2 Review Of Design/Manufacturing/Service Information

Indicators and Risk Factors can be inferred from a review of the typical design and manufacturing and service information for the equipment. Information may need to be gathered from several different sources. The key data required for review includes:

(a) Design and manufacturing data

- Design parameters (dimensions, drawings, design pressure, max and min design temperatures, design life/cycles, tolerances, stress concentrations, weld details).
- Materials (specification, properties, welding procedure, qualification tests).
- Design verification (Code calculations, stress/fatigue/creep analysis, limits)

- Manufacturing quality (Non conformance, concessions, heat treatment records).
- Manufacturing inspection (Scope, technique, acceptance standard, defects, repairs).
- Manufacturers operating and maintenance instructions.

(b) Service data

- Operational history (Process conditions, contents, pressure/temperature cycles, time at elevated temperature, vibration, shutdown).
- Maintenance history (Seal/gasket replacements, paints and coatings, valve/level gauge testing/calibration, pipe hanger load setting, descaling and decoking).
- In-service inspection (Scheme, technique, acceptance standard, thickness measurements, defects, repairs).
- Fitness-for-service assessments (Fatigue and creep assessments, fracture analyses).

Tables 3a and 3b on pages 63 and 64 summarise the indicators and risk factors that can be determined from such data.

(c) Competence and management records

Available documentation can also indicate the level of competence and management within the organisation responsible for the equipment. The type of records that should be available include the quality plan (and whether ISO certified), audit reports, and written procedures of work. There should also be training records for staff, and risk assessments for all the work procedures. Although this kind of documentation will not directly affect the assessment of ageing, it gives an impression of the attitude to keeping and maintaining documentation, and following codes and procedures.

(d) Absence of information

A complete set of records for equipment design, manufacture and operation will help you to determine the likely damage mechanisms and remanent life. A lack of information introduces uncertainty, and makes the assessment of damage due to ageing more difficult. Good companies will retain records about their equipment, which can enable their equipment to be operated with more confidence and for longer.

Records may be unavailable for many reasons. For example, significant amounts of equipment history can be lost when paper record keeping is transferred to or between computerised systems. The temptation for a modest cost saving on data transfer, can lead to the irretrievable loss of service history.

3.3.3 Indicators/Risk Factors Of Premature Or Accelerated Ageing

The traditional pattern of deterioration, damage and failure of equipment throughout its life is described in the Stages of equipment lifecycle earlier in the report (see Section 3.1.1). While the time-scales and rates of ageing for different items of equipment can be very variable, major maintenance and overhauls can extend the period of the predictable stable Stage 2 operation after a further period of bedding down when steady conditions are reached again. With periodic maintenance, sustained performance and integrity of equipment over a long life can be expected.

Within the pattern of failure described, there are factors that will accelerate or promote premature deterioration of equipment in service. These are listed in Table 4. By developing an understanding of these factors and their origins, steps can be taken to eliminate them. These factors have been categorised into groups within Table 4 relating to the source of the accelerating influence. These are not definitive categorisations, as there will be potential for factors to arise in a number of situations (e.g. construction and maintenance similarities).

This list includes factors from many years of operating experience, which may give the appearance of a daunting management task to control. It must be viewed in the context of assessing criticality, to prioritise effort in maintaining integrity. Examples from each grouping of sources of accelerating influences are given below Table 4.

3.3.4 Indicators From Rotating Machinery

While rotating machinery such as centrifuges, circulators and pumps may not form part of the containment boundary beyond the seal, failure of this machinery can impact the containment. You should therefore be alert for the signs of impending failure. These could include excessive noise from the bearings, vibration, overheating, leakage, interference of the rotating and static parts, and loss of power or effectiveness.

Table 3a Indicators/risk factors that can be inferred from design and manufacturing data

Document	Indicator/Risk Factor
Equipment specifications and orders	Enables comparison of maximum permissible loading, service life duration, operating conditions with actual duty in service
Design drawings	Enables quantification of any changes in dimensions measured in-service from design, and can be used to identify design features that could be susceptible to fatigue or corrosion
Material specifications, compositions and mill certificates	The material specification and mill certificates allow confirmation that the correct material was used. High hardness indicates a risk of certain defects (e.g. hydrogen cracks or lamellar tears), and potentially low fracture toughness.
Codes and standards assessments	For example, minimum thickness calculations, fatigue design assessment, corrosion allowances, heat treatment requirements, and use of BS7910 [H2] to assess fabrication quality and set defect acceptance criteria. This will demonstrate the extent of compliance of the equipment to known standards and set limits
Manufacturing reports and inspection test reports	Shows whether there were any non conformances or manufacturing defects from start of life
Welding records	Welding procedures and qualification can provide confidence in the quality of the welding and can indicate whether any part of the weld may be susceptible to defects.
Stress relief and heat treatment records	Indicates whether high residual stresses may be present, which could be a factor in causing cracking when in corrosive environments or under static or cyclic loading
Manufacturer’s instructions to owners/users	Enables users to assess whether equipment is being operated correctly

Table 3b Indicators/risk factors that can be inferred from service data

Document	Indicator/Risk Factor
Installation and commissioning report	Problems encountered during installation and commissioning of equipment may lead to further problems later in its life. This may allow identification of latent problems due to poor fit-up.
Written schemes of examination	Confirms how often and how thoroughly the equipment has been examined throughout its life
Reports of examination	The results of any previous examinations will provide an indication as to the current condition of the equipment in relation to its length of service, will highlight any defects detected.
Reports of repairs	The reason for, or recurrence of, repairs may indicate potential ageing problems. The repair itself may also introduce further defects.
Operational history and process history	Shows if the equipment has been used under different operational conditions earlier in its life that may have initiated corrosion or defects that will increase the risk of ageing later in life
Maintenance records	Show whether the equipment has been properly maintained during life and may indicate reoccurring problems. Lack of evidence or detail would suggest that the equipment has not been properly maintained and could be prematurely aged
Quality of NDT and inspection reporting	Indicates the size of undetected defects that may still be present after NDT
Safety consequences and risk assessments	Helps to identify risks from failure as a result of degradation
FFS assessments to codes	May indicate the risk of fracture and/or remaining fatigue life from the when the assessment was carried out.

Table 4 Factors promoting premature or accelerated ageing

(a) Design and construction (including fabrication and installation)

Accelerating factor	Resultant effects
Excessive force to (typically) fit pipework	Misalignment of flanges and uneven gasket sealing, high loading on pipework. Deformation of bellows
Misalignment of vessels	As above. Also uneven fluid distribution in exchangers
Uneven bolting of flanges	High flange loads; flange leaks
Errors in design, fabrication and installation	Stagnant areas. Complex pipe routing leading to air locks and non-draining. Pipework hammer.
Inappropriate storage of equipment	Corrosion prior to installation. Mechanical damage. Contamination of surfaces.
Use of contaminated water for pressure testing	Corrosion damage during pressure testing. Sensitisation to further corrosion damage due to (e.g.) pitting. Corrosion/blockage in service due to residues (possibly leading to overheating). Fouling/corrosion due to biologically active species.
Failure to remove transport stays (particularly on bellows)	Overloading of pipework or vessel. Damage to rotating equipment
Incorrect, inadequate or ineffective vent systems	Backflow from vent or into vent from contents & corrosion. Vacuum damage from reduced pressure
Local environment influences	E.g. sea estuary vs. inland, undergrowth, cooling tower drift, steam trap release, adjacent leaks, can all be environments which promote local corrosion.
Crevices or dead spaces from design / manufacture	Local environments created which may cause or accelerate corrosion
Inadequate support of small bore connections	Vibration and fatigue

(b) Commissioning

Accelerating factor	Resultant effects
Over filling equipment due to lack of knowledge or calibration	Deterioration of safety items; e.g. contamination of relief valves, flame arrestors etc. Blockage or deposition in associated systems
Poor control in firing of heaters	Risk of damage to refractory linings. Overheating of internals and pressure boundary
Residual contamination in equipment	Blockage and associated problems such as overheating. Corrosion (similar effects to using contaminated water on pressure test, see above)
Poor process control	Operating conditions outside design limits, risk of excessive forces/temperatures causing damage or failure.

Table 4 cont…

(c) Operation (direct control of plant)

Accelerating factor	Resultant effects
Poor water treatment	Corrosion (similar effects to using contaminated water on pressure test, see above). Fouling and blockage causing overheating.
Thermal transients	Thermal fatigue loads. Mechanical stressing.
Poor flow control	Risk of fouling / deposits and blockage. Erosion. Cavitation. Water or steam hammer causing fatigue.
Temperature control (may be linked with flow control)	Increased corrosion rates. Risks of contaminant concentration mechanisms. Risks of condensation. Potential for sub-zero exposure (brittle fracture or freezing damage). Overheating traced lines.
Hot or cold starting	Thermal cycling and fatigue. Overstressing of components through expansion & contraction.
Control of "idle" or temporary off line periods	Corrosion due to stagnant conditions. Ingress of air or moisture to 'dry' systems. Stratification in tanks. Freezing damage

(d) Operation (indirect or external influences)

Accelerating factor	Resultant effects
Trace elements	E.g. chlorides or caustic in services (water, steam, air) causing local corrosion or cracking
Trace contamination or impurities in feedstock / product	Local corrosion or cracking. Product contamination. Risk of solids or sludge build up.
Change of feedstock source	Influence on plant control & performance with potential for deterioration.
Supply interruptions (services, raw materials)	Cyclic running or rapid / uncontrolled plant shutdown
Poor or inadequate instrumentation	Control parameters exceeded
Effects of agitation or stirring	Locally increased flow rates

(e) Maintenance

Accelerating factor	Resultant effects
Poor understanding of equipment by maintenance resource	Increased risk of deterioration or leakage after maintenance
Lack of specification of modification or repair	Increased risk of deterioration of repairs, failure of repairs.
Retightening high temperature bolting	Shortened life of bolting or gasket
Changes of spares supplier	Risk of reduced integrity from inferior components
Defects or residue after maintenance	Increased risk of corrosion or blockage in plant
Poor control of hydraulic pressure testing	Residues of water may cause corrosion. Deterioration of 'fragile' equipment by stressing

(f) Control of modifications

Accelerating factor	Resultant effects
Equipment modification	Design may be outside original limitations
Operating modification	Operation may be outside original limits

3.4 INSPECTION AND NON-DESTRUCTIVE TESTING

3.4.1 Approach To Inspection Strategy Over The Four Stages Of Equipment Life

Inspection for damage is a key activity for all equipment containing hazardous fluids and/or pressure where the maintenance of containment integrity is vital for continued safe operation. This is particularly so as equipment deteriorates, but inspection is important at all stages of the life cycle. The approach to inspection will depend on the Stage of equipment life that has been reached, but as a guide, Appendix 3 gives a general methodology for inspection that applies at all Stages. Appendix 4 provides information on the capabilities/limitations of various NDT methods/techniques.

Figure 5 below identifies the types of inspection approach that are appropriate at the different stages. Early in life (Stages 1 and 2) the approach to inspection is generally confirmatory. Later in life, (Stages 3 and 4) a more deterministic, quantitative, approach is advisable.

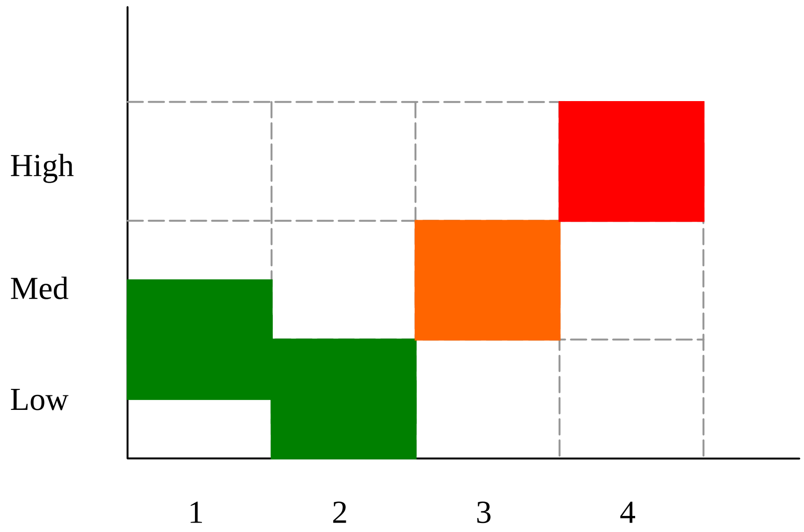

Figure 5 Approach to inspection at the different stages of equipment life

Before equipment enters service, it is good practice to have drawn up a scheme of future examination designed to detect damage due to potential deterioration mechanisms in the areas where they are most likely to occur and cause danger (see Case Study 10). Duty Holders for pressure systems have by law to possess a written scheme of examination drawn up or approved by a Competent Person (PSSR 2000 [A3]), except when the pressure volume product is less than 250bar-litres. The scheme needs to schedule the first thorough examination after entering service and subsequent examinations as far as these can be foreseen.

It should be noted that where there are many, often complex, components within a plant, the approach to the focussing of the inspection effort is best based on an assessment of component criticality. This should be part of an on-going risk assessment throughout the life of the equipment and is highlighted, below.

Stage 1 - Confirmatory - first thorough (finger-print/benchmark) inspection

When equipment is in its Post-commissioning ('Initial') Stage, the most likely faults arise from major shortcomings in the material, design or manufacturing, or from installation, commissioning or early operation errors. New equipment does not preclude the possibility of pre-mature damage. During this stage, it is good practice to carry out a thorough 'finger-print/benchmark' inspection. This should be able to confirm the expected integrity of the equipment and to identify any problem areas.

The timing of the first in-service inspections may be determined from either a risk assessment or industry recommendations [F1, F2]. They should be of a form that will allow comparison with results from in-service inspections carried out during the later stages of life. For example, it might be important to measure the original wall thickness of parts expected to corrode in-service, the absence of defects in certain welds where fatigue could occur, or the size of any detected manufacturing defects that might be expected to grow.

The nature of the inspection is confirmatory. Inspection is carried out to confirm what is expected about equipment condition (from the design assumptions and inspections during construction). Routine inspection methods/techniques and generic inspection procedures are generally used. For inspection personnel, recognised third party certification/'in-house' programmes of training and examination, covering the appropriate inspection methods/techniques, will usually be all that is required. Inspection performance requirements will, in general, be less demanding than for the later stages of service life. Examples of confirmatory inspection include:

- Manual ultrasonic thickness measurements to confirm wall thickness;
- Magnetic particle inspection to confirm the absence of surface cracks in a weld;
- Visual examination to confirm the absence of physical damage or obvious flaws.

These types of inspection will normally be part of the scheduled inspection programme. For pressure equipment falling under PSSR 2000, they will be detailed in the Written Scheme of Examination. The use of more advanced techniques may be appropriate for specific components.

Stage 2 - Confirmatory - risk-based inspection

As the equipment enters Stage 2 (Risk-based, or 'Maturity'), most of the initial (unexpected) integrity issues should have been dealt with and the equipment should be in its most stable operating regime. The first thorough inspection will have set a baseline for the condition. It may now be possible to extend inspection intervals through a risk-based analysis of degradation, failure likelihood and consequences. HSE Research Report 363/2001 - *Best practice for risk-based Inspection as a Part of Plant Integrity Management* [F4] gives guidance on this process.

When inspections are made, the nature of these is still confirmatory as no damage or defects will generally be expected. Routine inspection methods/techniques may still be used with generic inspection procedures, but good inspectors will be alert for the unexpected at potential trouble spots. Monitoring of operating parameters may be appropriate to confirm expectations that the equipment remains within the design envelope, particularly if the operating environment is variable or uncertain.

Stage 3 - Deterministic - quantitative inspection

As the equipment starts to enter Stage 3 (Deterministic, or 'Ageing'), damage and the likelihood of equipment failure increase. During this stage a more deterministic approach to inspection is appropriate. This approach to inspection is carried out when there is insufficient knowledge or prior experience to support integrity, when the evidence of deterioration starts to increase, or when a previous integrity issue has arisen in the item or a similar item of equipment. The prime objectives of a deterministic inspection are:

a) To detect the onset of damage.

b) To determine the current condition quantitatively.

c) To determine the extent of damage that has occurred, and

d) To determine the current rate of ageing.

This information will be needed to assess fitness-for-service, residual life and to set a future inspection strategy. Here, inspection has become a major part of the integrity case for the equipment and greater confidence is needed in its capability and delivery.

Deterministic inspection uses inspection methods/techniques that are, in general, more advanced, and inspection procedures that are more specific and thorough than those used during the confirmatory phase. Inspection performance requirements may demand much more accurate sizing and location of defects (with high confidence) for fitness-for-service assessment purposes. With regard to inspection personnel, individual qualification on a representative test piece may be required to ensure that high reliability can be achieved.

Examples of deterministic inspection in Stage 3 include, semi/fully-automatic ultrasonic weld inspection to determine the extent of fatigue damage, or eddy current inspection to determine the extent of stress corrosion cracking in a stainless steel vessel. These types of inspection would probably not be part of the scheduled inspection and maintenance programme. Where ageing is active, repeat inspections at an appropriate frequency may be required to determine the rate of degradation.

Stage 4 - Deterministic - monitoring inspection

As the end of equipment life approaches ('Terminal'), the equipment will be in a potential or actual damaged condition. A lot of reliance, therefore, will need to be placed on inspection data to justify continued operation. During this stage of equipment life, inspection should be routinely deterministic supported by regular component monitoring.

Here the objective is to ensure that a suitable minimum safety margin exists between the current equipment condition and a limiting condition beyond which the equipment may be potentially unsafe. During this stage, inspection and monitoring may tend to be more frequent and the accuracy of measurement is even more of a key requirement. For components approaching the minimum safety margin, continuous/on-line monitoring may be appropriate.

3.4.2 General Remarks On Detection And Sizing Of Defects And Damage

This Section of the report describes how NDT can be used to measure the extent of wall thinning, cracking and other defects and damage indicative of ageing equipment. The use of quantitative NDT techniques such as Manual Ultrasonic Testing, Corrosion Mapping, Time of Flight Diffraction (TOFD) and Phased Array are discussed in the context of issues concerning technique capability and inspection reliability. NDT methods suitable for particular types of damage are highlighted.

Section 3.4.9 gives a summary of NDT methods suitable for the detection, sizing and assessment of different types of damage. The summary is not meant to be exhaustive. Some NDT methods will not be suitable under certain operating conditions.

Note that the HSE has produced a series of 'Best Practice' NDT Guides [G2]. These cover the procurement and conduct of manual ultrasonic inspection, and penetrant and magnetic particle inspection (a guide on industrial radiography is also to be published). Implementation can assist in improving the reliability and sizing accuracy of NDT measurements.

3.4.3 Visual Examination And Surface NDT Methods

The simplest forms of damage to external or internal surfaces can be detected using visual inspection by a trained inspector. Certification for visual inspection is available under the PCN (Personnel Certification in NDT) scheme. Guidance on the competency and health requirements for inspectors is available from SAFed.

While most visual inspection is on areas directly visible to the eye, areas that, due to access restrictions are inaccessible can sometimes be inspected using magnifying boroscopes/endoscopes/photography. Sizing of the damage may be made using simple tools such as a ruler or mountable travelling microscope.

Visual inspection is, however, limited to damage that is clearly visible on the surface of the component (e.g. surface damage, pitting, scratches, dents, gouges, general wall thinning). While visual inspection may provide a measure of the damaged area, it does not usually provide any information about the through-wall-extent of the damage. This is normally the more important dimension for structural integrity assessment.

Surface damage that is not clearly visible, such as cracking, may be revealed using NDT methods such as dye penetrant and magnetic particle testing. Both these methods are relatively straightforward to apply; many inspection bodies carrying out the duties of Competent Person train and certify their surveyors to apply these methods at Level 1 under a company based (second party) scheme. However, like visual examination, they only enable a measurement of the length of the damage at the surface and not through-wall-extent.

If data for fitness-for-service (FFS) assessments are required, then these types of NDT do not provide all the required information i.e. an accurate determination of surface flaw length and through-thickness-extent. The usual and often best way of obtaining this information, reliably, is by use of an ultrasonic technique. Typical flaw sizing capabilities for the ultrasonic techniques detailed below are given in Section 3.4.9.

3.4.4 Manual Ultrasonic Testing

Ultrasonic testing (UT) is a volumetric method of inspection that can be used to detect buried as well as surface defects and to measure their through-wall extent. Manual ultrasonic testing is used extensively for detecting and sizing flaws such as cracks. It is also used to measure wall thickness and hence wall thickness loss. For example, it is used to ensure boiler shells have adequate thickness and are free from cracking that could cause a serious failure.

These days, modern ultrasonic flaw detection is now the norm for in-service inspection. Digital sets are replacing the old analogue sets and are extending the range of what is possible with manual ultrasonic testing. The technician can now store and retrieve calibrations, can measure signal range and amplitude very accurately using electronic gates, and can capture A-scan signals for off-site evaluation and reporting. For example, the measurement of bore-side oxide on boiler tubes to identify the tubes most susceptible to creep failure has been made possible with modern digital sets.

When applied to an external surface, ultrasonic testing can access defects located on the opposite inner surface, thereby removing the need for the inspector to gain internal access to the component. It can also be designed to ‘see’ around corners and obstacles. Care is needed to ensure that such ‘non-invasive’ ultrasonic inspection is performed with the required technical basis underpinning its use.

A series of trials within the Programme for the Assessment of NDT in Industry (PANI[4]) [G1] found that the reliability of manual UT using generalised procedures to detect and size defects that would be of concern in plant was highly variable. In some instances, normal manual UT procedures were inadequate. As a result, the following additional measures to improve the reliability of a manual UT are recommended:

- Use of specific procedures targeted at the particular component geometry and type/position/size of defect to be detected;
- Provision of additional training to NDT operators, both in the use of the procedure and trials on representative test pieces;
- Use of independent, repeat inspections;
- Only to use NDT operators who apply ultrasonic inspection on a frequent basis.

3.4.5 Semi/fully-automatic ultrasonic techniques

The use of semi/fully-automatic ultrasonic techniques (often in combination with a manual technique) can eliminate some of the human factor issues associated with manual ultrasonic testing and can improve reliability. This is mainly due to the real-time visualisation during scanning of the component being inspected and the recording of data for post-processing. Ultrasonic techniques that lend themselves to automation and which are now used (almost routinely) for the determination of component condition (including the accurate determination of flaw size for FFS assessment) are:

- Corrosion mapping.
- Time of flight diffraction (TOFD).
- Phased array.

While solving some reliability issues, semi/fully-automatic techniques create others associated with equipment set-up, data processing and the evaluation of data, which can often be complicated and require specialist technicians.

(a) Corrosion mapping

Wall thickness is often measured using manual ultrasonic testing using an ultrasonic probe and a flaw detector/thickness gauge. While these measurements can be very accurate, they are limited to the evaluation of uniform material loss within the area of the component designated for the inspection. By their non-uniform/isolated nature, corrosion types such as pitting cannot be measured with any reliability using manual ultrasonic testing. In order to improve

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[4] The 'Programme for the Assessment of NDT in Industry' (PANI) investigated the performance of manual ultrasonic testing as applied in-service. The Health & Safety Executive sponsored the programme and many of the UK's leading inspection companies participated. Test pieces representative of industrial plant components containing simulated in-service defects were produced. These were mounted in a way that represented typical on-site access conditions. An ex-service boiler, containing unacceptable defects, was also included in the population of test pieces. A round-robin exercise to detect, characterise, position and size the defects was then undertaken.

The results of the round-robin exercise showed a wide variation in defect detection and sizing performance.

In order to improve the performance of manual ultrasonic testing, PANI recommended the use of improved procedures and practice for operators on training samples prior to inspection. Following on from PANI, the Health & Safety Executive commissioned a second round-robin test piece exercise, PANI 2, aimed at assessing performance improvement following implementation of the recommendations of PANI. The PANI 2 programme was completed in 2003. Again, however, a wide variation in defect detection and sizing performance was observed.

Out of the PANI programme have come a series of Best and Recommended Practice Guides published by the Health & Safety Executive which contain recommendations for improving the reliability of manual ultrasonic testing, magnetic particle testing, liquid penetrant testing and industrial radiography. These guides are available for download on the HSE website.

detection for these, and all other corrosion types, it is preferable to use an automated corrosion mapping technique.

With corrosion mapping, the ultrasonic probe is continuously scanned over the component surface and wall thickness data is recorded and stored every few millimetres or so by the corrosion mapping system. After scanning is completed, the stored data is plotted in a wall thickness map (usually a plan view (C-scan) presentation). Each thickness level e.g. 25-23mm, 22-20mm etc. is then usually displayed as a colour on the C-scan allowing material loss by corrosion to be easily recognised. Because corrosion mapping is highly reproducible (typically within 0.5mm material loss) it enables accurate monitoring and accurate calculation of corrosion rates.

Corrosion mapping is used extensively in the petroleum/chemical industries where corrosion is a major issue. Its applications include vessels, pipework (bends), tank walls etc. Because of its high reliability, it is one of the few non-invasive inspection techniques that can be accepted in lieu of internal visual inspection of vessels/tanks.

(b) Time of flight diffraction (TOFD)

TOFD is used for the accurate sizing of flaw height and also, in certain situations, for the detection of flaws. 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 for detection and sizing, flaw orientation is not such an important consideration (as it is with the ultrasonic techniques that rely upon reflection). The principle of the TOFD technique is illustrated below:

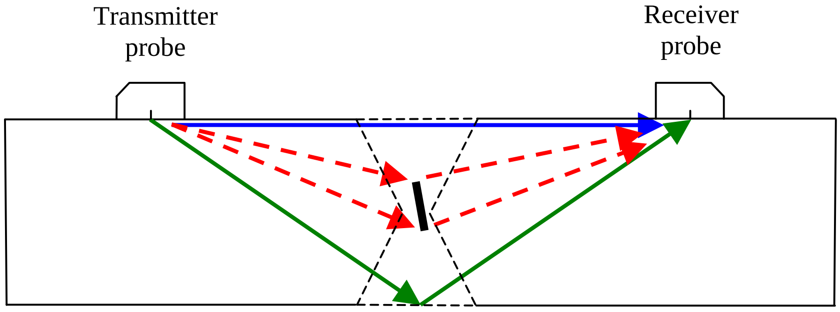

Figure 6 TOFD technique

The probes face each other at a fixed separation with one probe acting as transmitter and the other receiver in ‘pitch-catch’ mode. In the absence of a flaw, ultrasonic signals are observed from a lateral wave which travels between the probes along the scan surface and from the far surface (the back-wall echo signal). If a flaw is present, diffracted signals from the top and/or bottom edges of the flaw will also be seen, depending on whether the flaw is surface-breaking or embedded. The location and dimension of the flaw in the through-wall direction is found from the relative time delays between either the lateral wave or back-wall signals and the flaw tip signals.

Skilled NDT operators with specialist equipment and software capable of generating high-resolution images of the component will achieve the best results from TOFD. There are now many NDT operators who are trained and certificated (by PCN in the UK) to Level 2 in the set-up and application of the TOFD technique.

Scanning of the component can be performed in a variety of ways, ranging from manual scanning with encoded positional feedback (semi-automatic) for simple site applications, through to fully-automatic inspection for more complex applications. Scanning speeds of the order of 50mm/s are typical.

TOFD is ideally suited to the following:

- Accurate sizing of flaw height (± 1mm to ± 2.5mm)[5];
- Monitoring changes in flaw size from repeat inspections.

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 indications from a flaw in these zones. The depth of these zones is dependent on the probes and separation used. In addition, TOFD may not detect unfavourably orientated flaws, and certain flaw types and small flaws in, for example, 'dirty' steels, and can sometimes mimic more serious flaws such as cracks. Because of these limitations, TOFD is best used for flaw sizing.

(c) Phased array

This technique uses arrays of single element transducers (as used with the other ultrasonic techniques) that have been subdivided into small segments or elements. A phased array probe can contain up to as many as 128 elements. By sequentially 'firing' each element in the array a wavefront is created that follows a specified beam angle. The angle of the wavefront can be changed by altering the firing sequence.

Phased array ultrasonic testing is finding a wide range of applications such as the inspection of complex geometry components and/or where access for scanning is limited, in certain situations, enabling defects to be detected and sized without physically moving the probe. In addition, it is possible to generate a focused beam to 'pin-point' the location of a defect in a small component such as a fillet weld, for example, or to detect a particular defect at a specific location.

Data from phased arrays can be displayed in 'azimuthal' format, a unique display format characteristic of phased array inspection. Note, to generate this display, the probe does not need to be moved; scanning being effectively carried out by 'sweeping' the beam through a number of generated beam angles, e.g. 30-60°.

Phased array systems range from the small and portable to the larger very powerful and expensive systems which have found application in the power generation industries for the inspection of heavy wall components and difficult to inspect materials such as stainless steel welds. PCN is able to offer certification for operators in the set-up and application of the phased array technique.

3.4.6 Other NDT Techniques

While this Section of the report has focused mainly on the ultrasonic techniques, there are a number of other NDT techniques that are used for detecting and characterising ageing damage. These include real-time radiographic imaging, thermography, acoustic emission, flux leakage techniques and techniques for detection of corrosion under insulation. They are briefly described below. The capabilities/limitations and applications of these techniques (and others) can be found in Appendix 4. Information on other NDT techniques is given in [F3]. These include ultrasonic attenuation/ backscatter/velocity measurements for hydrogen and/or creep damage measurement.

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[5] Depends on the particular test situation. Under laboratory-type conditions, ± 1mm is very achievable. Under site conditions, ± 2.5mm is more realistic.

(a) Real-time radiographic imaging

Where it is not practical to remove insulation from pipework, real-time radiographic imaging is an inspection technique that can be used. The presence of external surface corrosion under insulation (CUI) can be detected using the tangential technique. Measuring (double) pipe wall thickness can detect both external and internal corrosion and pipe blockages. Good access around the pipe is required.

(b) Thermography

Thermography is a remote inspection technique that produces a heat picture of the surface of a component using special infrared cameras (imagers). It has a wide range of applications, including the inspection of insulated pipework and vessels for potential corrosion under insulation sites. Where pipes are carrying heated fluids, thermography can detect locally thinned areas, as these will tend to get hotter than surrounding thicker material.

(c) Acoustic emission

Acoustic emission is an inspection technique that can be used to detect and monitor flaws by subjecting the component to an applied stress, for example during a hydrostatic test. Specialists are required to provide and apply the equipment, and to interpret the results. The technique is best used for screening large structures, such as storage tanks, for gross defects.

(d) Flux leakage techniques

Techniques such as Magnetic Flux Leakage (MFL) and ‘improved’ MFL, Saturation Low Frequency Eddy Current (SLOFEC) can detect corrosion in pipework. SLOFEC can detect damage at greater depths and through thicker coatings.

(e) Techniques for inspection of corrosion under insulation

Corrosion under insulation (CUI) is a major concern in the petrochemical industries and there are a number of specialist techniques available for its detection. These include creeping head waves, long range guided wave ultrasonics, and profile radiography. These techniques reduce the need to remove large areas of insulation and coverage rates can be high.

These techniques must, however, be capable of meeting the relevant inspection performance requirements. Demonstration of capability is particularly important, as experience is limited. This can be done, either by carrying out practical trials, or by comparison with the results from previous inspections where damage was detected.

3.4.7 Information For Assessment Of Damage And Fitness-For-Service

The assessment of damage and fitness-for-service requires knowledge of the current extent of the damage, the rate at which the damage has been occurring, and a prediction of damage rate in the interval to the next inspection. The rate of ageing (trend) may be determined by sizing the damage at appropriate intervals during service and measuring the change. These intervals may need to become more frequent if the damage rate is increasing. For most FFS assessments, the accurate determination of flaw height will be required. Typical sizing capabilities for the ultrasonic techniques detailed above are given in the following table:

Table 5 Flaw sizing errors for different NDT techniques

Ultrasonic technique	Sizing accuracy	
	Flaw height	Flaw length
Conventional manual ultrasonics (e.g. weld testing)	± 5-6mm*	± 10mm
Conventional manual ultrasonics (e.g. corrosion assessment)	± 1mm (depth)	
Corrosion mapping (applied semi/fully-auto)	± 0.5mm (depth)	
Phased array (applied semi/fully-auto)	± 3mm	± 10mm
TOFD (applied semi/fully-auto)	± 1-2.5mm	± 10mm/5mm**

* From PANI 2 results [G1].
** Synthetic Aperture Focusing Technique.

Note 1. The values given in the table above are typical values for sizing accuracy. By carrying out a specific inspection qualification exercise it may be possible to generate values for a technique that are better than those given in the table above.

Note 2. The above values (or possibly better values) need to be taken into account when assessing the rate of component ageing to avoid any mis-interpretation e.g. a component thickness appearing to increase between re-inspections based on the data from a manual corrosion assessment.

Note 3. For manual ultrasonic sizing, there is a need to consider the associated human factors issues. Generally, improvements in reliability can be realised by:

- *Implementing the recommendations of the HSE Best and Recommended Practice Guides [G2];*
- *Carrying out specific inspection qualification exercises;*
- *Using semi/fully-automatic techniques which have the capability to record and store data for processing and evaluation.*

3.4.8 Non-Invasive NDT

Most inspection requires direct access to a surface close to where the damage is situated and this often means opening up vessels and containers for internal access. Non-invasive inspection (NII) avoids this by using techniques where access to the equipment is from just one side and/or at position remote from the damage. It is being used increasingly in lieu of visual inspection for the detection of damage such as cracking and corrosion inside vessels and corrosion under insulation on pipework.

Without visual observation of a surface, increasing reliance is being placed on the non-invasive NDT methods, procedures and implementation. As non-invasive inspection is relatively new, caution needs to be exercised until sufficient favourable experience is built up. The HSE will be issuing Guidance on the application of NII for safety critical equipment.

3.4.9 Detection And Sizing Of Damage Types And Mechanisms

The following table lists the types of damage caused by of some of the most common degradation mechanisms found in equipment containing hazardous fluids or pressure, and identifies NDT methods and techniques suitable for the detection of each type of damage. It should be noted, that the methods/techniques identified in the table below may not be appropriate for certain components operating under certain conditions, nor is the listing of methods/techniques meant to be exhaustive. Reference to the selection of the most appropriate method/technique can be found elsewhere in the report. Appendices 4 and 5 describe the methods and techniques for further information.

Given detection of a type of damage (e.g. cracking, general corrosion), understanding and assessment of the damage mechanism and underlying root causes is a necessary step before further action can be taken. In some cases this will be obvious, and in others less so. Where the mechanism is in doubt, there is benefit from using materials engineers specialist in failure analysis with appropriate laboratory facilities.

Table 6 Methods of inspection for the detection of various damage mechanisms

Ageing damage	Example degradation mechanism	NDT methods/techniques used for detection/assessment
Blisters	Defective coating	(1)
	Hydrogen absorption	(6), (9), (11) & (12)
Scaling (boiler tubing)	Precipitation	(1)
Blockages (piping)	Various (internal) e.g. fouling	(17), (18), (21) & (26)
Cavitation	Creep damage	(31)
Cracking	Corrosion fatigue	(1), (6), (9), (11), (12), (17) & (23)
	Creep damage	(1), (3), (6), (9), (11) & (12)
	Fatigue	(1), (2), (3), (4), (6), (7), (8), (9), (11), (12), (17) & (23)
	Hydrogen absorption	(6), (9), (11) & (12)
	Stress corrosion	(1), (2), (3), (4), (6), (9), (11), (12), (17) & (23)
Dents/gouges	Various (external) e.g. impact damage	(1)
Embrittlement	Hydrogen absorption	(6), (9), (11) & (12)
Fretting wear	Vibration	(1), (4) & (30)
Holes	Various (internal/external) e.g. local corrosive attack	Vessels/tanks: (1), (2), (4), (14) & (27) Piping: (1), (2), (4), (17) & (26) Tubing: (1), (4), (15), (16) & (17)
Wall thinning (general)	Corrosion	General: (1), (6), (10), (13), (17), (20), (23) & (25) Tubing: (4), (15), (16) & (17)
Wall thinning (local)	Corrosion Corrosion under insulation (CUI)	General: (1), (10), (17), (18), (19), (20), (21), (23), (24) & (25) Pitting (small): (1), (2), (10), (17) & (23) (4), (15), (16) & (17) – Tubing Pitting (large): (1), (10), (17), (19), (20), (21), (23), (24) & (25) (19), (20), (21) & (22)
	Erosion	Pipe bends (6), (10), (13), (17), (20), (24) & (25) Weld root (6), (9), (11), (12) & (17) Tubing(4), (15), (16) & (17)

Key for Table 6:

Main NDT methods:	Specialist NDT techniques:	Screening techniques:	Other techniques:
(1) Visual Inspection – may include use of magnification and endoscopes (2) Penetrant Testing (3) Magnetic Particle Testing (4) Eddy Current Testing (5) Radiographic Testing (6) Ultrasonic Testing	(7) Alternating Current Field Measurement (ACFM) (8) Alternating Current Potential Difference (ACPD) (9) Time of Flight Diffraction (TODF) (10) Ultrasonic Corrosion Mapping (11) Automated Ultrasonic Pulse-echo (12) Ultrasonic Phased Array (13) Ultrasonic Continuous Monitoring (14) Spark Testing (15) Internal rotary inspection system (IRIS) (16) Remote field eddy current (RFEC) (17) Remote visual inspection (RVI)	(18) Thermography (19) Long Range Ultrasonics (20) Pulsed Eddy Current (21) Real-time Radiographic Imaging (22) Neutron Backscatter (23) Acoustic Emission (AE) (24) Magnetic flux leakage (25) Saturation low frequency eddy current (SLOFEC)	(26) Acoustic Ranger (27) Leak Testing (28) Strain Gauging (29) MAPS (30) Vibration Measurement (31) Metallographic replication

Note, the capabilities/limitations of the above NDT methods/techniques for the detection of ageing can be found in Appendix 4.

4 ADDRESSING AGEING

4.1 WHAT ARE THE OPTIONS?

Once the existence, extent and mechanism of damage in a component of equipment have been established, a range of options is available. These include:

- Scrap and decommission the equipment, with or without replacement.
- Remove the damage, with or without a repair.
- Repair the component, temporarily or permanently, with or without removing the damage.
- Analyse the margin between the component condition and minimum code specification.
- Undertake a fitness-for-service and/or remanent life assessment (if defect size data exists).
- Change operating practises, de-rate the duty, or make favourable modifications to process conditions or chemistry.
- Monitor the component to ensure that the extent and rate of the damage do not change sufficiently to compromise safety limits.

Several of these actions may be needed to manage the problem; they are not mutually exclusive. The course of actions needed will usually depend on the nature of the damage, economic factors associated with the operation and repair/replacement of the equipment and the costs of assessment and monitoring. It may be necessary to use appropriate expertise to assess the situation and decide what to do. In many situations, an initial assessment of fitness-for-service can indicate the most cost effective and safest course to take.

Sometimes defects in components and welds will be attributable to manufacturing, and may show no signs of further development. The existence of stable pre-service defects does not necessarily mean that the equipment is sufficiently safe and fit for further service. Some further action is always needed to ensure that adequate margins against failure exist.

Sections 4.2 and 4.3 cover fitness-for-service assessment and repairs. Section 4.4 discusses the revalidation of equipment as a result of changes during service. These may be due to:

- Modifications and repairs.
- Exceeding design life.
- Changes or margins between the original and current design codes.
- Changes in service conditions or duty.
- Proposed re-use of equipment, second hand or from storage.
- Accumulated industry experience and knowledge.

Where further service is envisaged, there is a need to review the scheme of examination, and maybe to monitor the damage or initiating factors. Information on this is provided in Section 4.5. The decision to end life is invariably an economic one, and an approach to the financial evaluation is given in Section 4.6.

4.2 ASSESSMENT OF FITNESS-FOR-SERVICE AND REMANENT LIFE

4.2.1 When To Assess Fitness-For-Service And Remanent Life

Fitness-for-service (FFS) assessment (also known as Engineering Critical Assessment or ECA) is a re-evaluation of the structural integrity of an item of equipment for further service, taking into account damage and deviations from design basis. The assessment of fitness-for-service and remanent life can be made at any stage once the type, scale and rate of the deterioration mechanisms have been identified or postulated. Case Study 11 in Appendix 2 illustrates the potential benefits of FFS assessment.

Fitness-for-service assessment can be carried out:

- During design.
- During service before damage has been detected.
- Once damage has been detected.

During design or before damage has been detected in service, it is necessary to postulate the occurrence of damage, and its subsequent evolution, using, for example, NDT reporting levels, existing test data or experience. When damage is detected in service, the actual scale of the damage as measured from NDT can be used. The rate of damage accumulation may be estimated from measurements repeated over a period of time, but be aware that historic trends are not always a good indication of future behaviour. At all stages, the objectives of carrying out a FFS assessment are to determine whether the equipment is safe in its current condition, and if so, what is its predicted lifetime given that further damage may occur, and to install a suitable inspection and monitoring programme.

If a FFS assessment has been carried out in the past, it is important to consider whether the results are still valid. It may be that the assessment procedure used previously has been revised or superseded, so that the same assessment carried out to current standards might give different results. Materials properties can also change over time due to mechanisms such as hydrogen embrittlement or temper embrittlement in steels. Therefore, although the recommendations of the original assessment would have been valid at the time, they may no longer be justifiable, even if none of the operating conditions have changed. An overview of the input data required for carrying out a FFS assessment is given in Figure 7.

4.2.2 Assessment Of Remanent Life

The remanent life of a piece of equipment can calculated from a number of sources of information, which are listed below. Although some calculations will be relatively simple and code-defined, there are also FFS procedures which can be more complex, and require specialist advice. In certain cases, knowledge-based judgements will be acceptable for estimating the equipment's remaining life.

Some of the key factors for assessing the remanent life include:

- Original design life (specified in years or number of operating cycles).
- Current equipment age and condition.
- How long ago the damage initated and how fast it is accumulating.
- Rate of degradation (whether constant, variable, or exponential).
- Expected operating regime and degradation mechanisms.
- Changes in material properties.
- Fatigue life (based on the S-N design or fracture mechanics).

- Corrosion life (determined from the corrosion rate, allowance and thickness limit).
- Limits determined from design or fitness-for-service assessment.
- Safety margins.

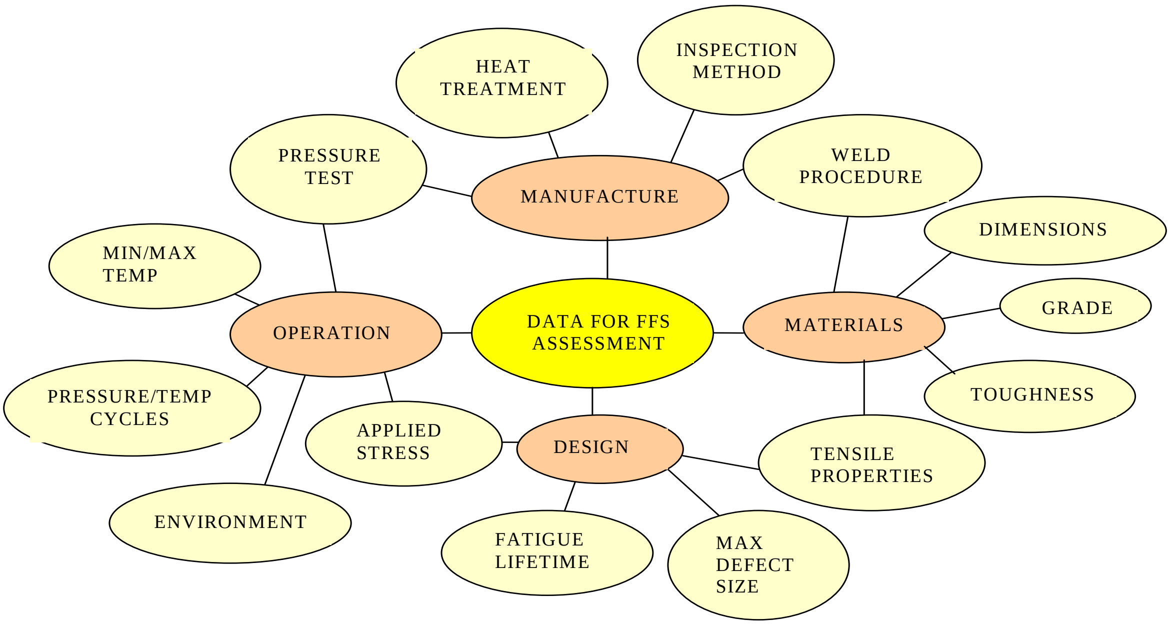

Figure 7 Data required for carrying out fitness-for-service assessment

4.2.3 Published Assessment Procedures

Procedures for assessing the fitness-for-service of equipment containing defects or damage have developed since the late 1960's and there are now many procedures available for engineers to choose from. Two of the most commonly used are:

- BS 7910 (2005): Guide to methods for assessing the acceptability of flaws in metallic structures [H2].
- API Recommended Practice 579 (2000): Fitness-for-Service [H1].

These and other FFS assessment procedures are referenced in Section 1.11. Other FFS procedures include R5 [H4] and R6 [H3] for the assessment of defects in equipment at high temperatures and HSG 93 [H11] for the assessment of pressure vessels operating at low temperature (discussed in Section 4.4.4(a)). ASME B31G [H6] is a procedure for the assessment of damage in pressure piping and pipework. Some of the simpler assessment procedures from codes such as API 579 [H1], BS 7608 [B6], BS 7910 [H2] and ASME B31G [H6] are included in the ENGfit toolbox software [F14]. Freely available to download, this is collection of code-compliant integrity tools for pressure equipment, designed for inspectors and plant engineers.

BS 7910 is published by British Standards for application to metallic structures across a range of industries. From its origins in PD 6493, BS 7910 is strongly orientated towards the assessment of defects in and around welds, and its most detailed procedures are for the assessment of fracture, fatigue and creep crack growth. Other failure modes, such as environmental cracking, and locally thinned areas due to corrosion in pipes and pressures vessels, are covered at a guidance level.

The American Petroleum Institute prepared API 579 specifically for assessing equipment in the refining and petrochemicals sectors designed to ASME codes. The procedures and supporting data relate to ASME design specifications and materials and are consistent with the design philosophy in terms of allowable stresses and factors of safety. A wide range of defect and damage types typically found during in-service inspection of refinery and petrochemical equipment are covered, with corrosion and thinned areas given prominence.

Other defects covered by API 579 include general metal loss, local metal loss and gouges, pitting corrosion, blisters and laminations, weld misalignment, dents and shell distortions, crack-like flaws, creep damage and fire damage. If used appropriately, the API 579 procedures have relevance for assessing types of equipment outside its intended scope, but it is the user's responsibility for their correct application on a case by case basis.

4.2.4 Choice Of FFS Procedure

The use of fitness-for-service assessment is now well established, although there is still a degree of reluctance to rely on it among some companies and regulators. The reasons for this are not clear. Users may gain confidence from the endorsement of FFS procedures by the American Petroleum Institute and British Standards Institution.

For non-nuclear equipment, API 579 [H1] and BS 7910 [H2] are the most commonly used procedures for FFS assessment. Both are recognised as safe and representing best practice, although they may not always give the same results. In many applications both API 579 and BS 7910 will be suitable. The choice may depend on company policy, or the attitude of the regulating authority, and access to the necessary data and sources of information, training and support. In terms of the advantages and applicability of the two procedures, the points in Table 7 can be considered.

Table 7 Comparison of API 579 and BS 7910

API 579	BS 7910
Intended for equipment designed using the ASME code and materials and gives results consistent with the original ASME design safety margins. May be used for equipment designed to other codes but users should be prepared to interpret the procedures in an appropriate manner.	Applicable to all metallic structures and materials and is written in a more generalised manner without reference to a particular industry, design code or material thereby allowing users to decide safety margins.
Covers a wide range of damage types typically found in refining and petrochemicals application, and gives procedures for different types of metal loss, physical damage, low and high temperatures, and crack like defects.	Deals comprehensively with fatigue and fracture of flaws in and around welded joints and gives annexes covering advanced aspects such as mismatch, mixed mode loading, residual stress effects and leak before break.
Designed at level 1 for use by plant inspectors and engineering personnel with the minimum amount of information from inspection and about the component. Levels 2 and 3 are for use by professional engineers.	BS 7910 requires some technical expertise in fracture mechanics and access to fracture parameter solutions and toughness data at all levels.

4.2.5 Assessment Levels And Competency Requirements

Both BS 7910 and API 579 offer three levels of assessment, but the detail of each Level differs between the standards. These are summarised in Table 8. BS 7910 has three levels only for fracture and fatigue analyses, API 579 offers three levels for all its analyses. The engineering and specialist competencies required in order to undertake assessments increase from Level 1 to Level 3, as the procedures become more complex.

Table 8 Levels of assessment in BS 7910 and API 579

	BS 7910	API 579
Level 1	Conservative screening procedure. Requires simple data and analysis. Can be used by qualified engineers without specific FFS training.	Conservative screening criteria. Minimal inspection/component information. Can be used by plant inspectors on site.
Level 2	Material specific data required. Analysis estimates the interaction between fracture and plasticity. To be used by qualified engineers trained in FFS assessment.	More precise evaluation than Level 1. Requires simple data & analysis. To be used by qualified engineers.
Level 3	Material specific data required. Analysis involves a direct calculation of plasticity effects. For use by qualified and specialist FFS engineers.	Detailed inspection/component information required. Analysis uses numerical techniques/FEA. For use by qualified and specialist FFS engineers.

4.2.6 Obtaining Materials Properties, Stresses And Other Data For FFS Assessment

Sometimes, the data required for a fitness-for-service assessment (such as material properties, service induced and residual stresses, and the damage) may not readily available. There are then several options available in order to generate this data.

(a) Material properties

If the type or specification of the material is not known, then an analysis of the chemical composition may be made. This will enable the key constituents such as the carbon content to be determined, and allow the material to be characterised. In the absence of specific material property data (e.g. tensile, fracture toughness), the options are to:

- Use the default (usually minimum specification) values for the material given in the appropriate code (e.g. API 579 for ASME materials) or in standards and literature.
- Locate the original mill sheet data, test reports, weld procedure qualification tests.
- Undertake laboratory testing, using material for the required test specimens taken from:
  - Archive parent and weld material
  - The original weld procedure test pieces (although this possibility is increasingly unlikely for older equipment)
  - Using the original welding procedure, parent material and consumables to replicate additional weld material
  - Material taken directly from the equipment. The location can either be left (if the material is taken from redundant structure) or repaired with a new patch or piece. There are many reasons why this is not feasible for equipment in continuous service, or if cutting pieces from the equipment would cause significant damage.
  - Extraction of a small amount of material taken using a semi-destructive method. Miniaturised test pieces can then be tested to generate the data (See Tables 8b and 8c).
- Undertake a test directly on the equipment using techniques that are effectively non-destructive (see Table 8a).

Table 9a summarises the testing techniques that can be used for measuring material properties and/or stresses without the need for removal of material. Table 9b gives some methods that can be used for material extraction, and Table 9c lists the test techniques that use miniaturised specimens. The tables are intended to provide a view of the available techniques, but are not exhaustive. Not all the techniques will be suitable for all materials, and some are still under development. You are advised to be cautious and take advice before using these methods.

Further practical advice on obtaining material property data is given in Section 4.2.16.

Table 9a Techniques for obtaining data for an FFS assessment using effectively non-destructive testing methods that do not require sample extraction

Technique	Details	Data measured
Strain gauging	Strain gauge consisting of metallic array is bonded directly to substrate. Data is logged and analysed	Stress, strain, fatigue stress spectra
Equotip portable hardness testing	Hand-held tube contains a spring-loaded hammer which strikes the surface. The rebound height is used to determine the hardness	Hardness, Approximate yield strength estimated from correlation.
Microdur hardness testing	Hand-held probe contains a Vickers diamond on the end of a rod. The change in the resonant frequency of the rod when a small indent is made is used to determine the hardness.	Hardness, Approximate yield strength estimated from correlation.
Instrumented indentation technique	Portable indentation machine mounted on surface. Multiple indentation cycles are used to plot tensile response.	Tensile properties (UTS, yield strength by extrapolation) Hardness
Centre hole technique	A controlled hole is drilled in the centre of a rosette of 3 strain gauges. The response is recorded and analysed.	Residual stress
Magnetic stress measurement system (MAPS)	A probe is placed close to the material surface. Several measurements are taken as a varying magnetic field is applied to the sample. Rotating the probe enables the principal stress axes to be determined.	Materials stresses, including residual stress

Table 9b Semi-destructive techniques for extraction of material from equipment in service for making small material test specimens

Technique	Details	Sample Extracted
Machining or cutting	Redundant material is removed from structure or excess thickness from convex surfaces using suitable cutting or machining equipment.	Depends on amount of material available/required
Boat sampling	Small wafer-like samples extracted from the component, leaving a smooth shallow profile	Thin elliptical samples 42mm x 26mm x 3mm size
Trepanning / EDM	Removal of full-thickness plug using a cutter or electro-discharge machining	Full-thickness round plug of material (from thick-walled vessels)

Table 9c Testing methods for obtaining data for an FFS assessment from small samples

Technique	Details	Data measured
Micro-tensile test	Testing of miniature (mainly flat) tensile specimens, monitored, for example by laser extensometers.	Tensile properties
Shear punch test	Cylindrical punch strikes a small disc specimen at constant speed.	Tensile properties
Miniature disc bend test	Bending of disc specimens using hemispherical punch	Tensile properties, fracture stress and strain
Small punch test	Disc specimen loaded in die-and-punch machine at slow rate using a steel ball contact. Test recorded by video monitoring.	Fracture appearance transition temperature (FATT) and fracture initiation toughness (K_{1c}) – not valid for all materials, tensile curve, creep rupture strength.
Compression tests	Small cylindrical specimen is compressed until failure (see ASTM E9)	Yield strength
Sub-size instrumented Charpy impact test	Small specimen is heated/cooled and then struck with hammer (see ASTM E28.07.07). Instrumentation records load-time curve.	Absorbed energy to fracture, lateral expansion, FATT, ductile/brittle transition (DBTT), nil-ductility temp, dynamic tensile & toughness initiation properties
Miniature fracture toughness testing	Small disc-shaped compact tension specimen (see ASTM E1737-96) or small CT specimen (ISO/TC 164/SC-N413) fracture toughness tests.	Single-point fracture toughness, tearing resistance curve

(b) Stresses

When a stress analysis is not available, it is usually possible to generate one using hand calculations or finite element analysis. When assessing fitness–for-service, it can be important to base the stress analysis on the as-built dimensions if these are different from the design drawings. Loads and constraints should represent the relevant service conditions, or be a conservative approximation. The degree of detail and mesh refinement need to be consistent with the use to which the analysis is being put. It is possible to produce FE models that include the cracks and other damage in equipment.

(c) Damage

Non-destructive testing techniques for detecting and measuring damage are discussed in Section 3.4 and Appendix 3.

4.2.7 Assessment Of Thinned Areas

Wall thinning can occur as a result of a variety of causes. Corrosion and/or erosion, wear, fretting and abrasion and over-grinding are among the most common. While published assessment methods of thinned areas are primarily with pressure systems in mind, wall thinning can and does occur on other critical and high hazard equipment, where similar assessment principles can be applied.

It is always important to understand the mechanism that has resulted in the thinning, since some mechanisms may also give rise to other types of damage. For example, over-grinding can introduce residual stresses that may make the site susceptible to stress related cracking or corrosion mechanisms. Some types of corrosive attack produce locally deep sub-surface pitting, or inter-granular corrosion, that can be difficult to detect but have the effect of reducing the effective load carrying thickness further. If any of these mechanisms are suspected, then additional assessment and/or remedial treatment may be necessary.

Thinned areas can be classified as general, local or pitting, and there are different analytical treatments available for assessing FFS for each type. API 579 [H1] gives a set of codified methods, mainly appropriate to equipment designed to ASME codes. These approaches may be adapted for use with equipment designed to other codes, but care is needed to ensure that the appropriate safety factors are maintained.

A simple analysis method is to assume that the effective wall thickness is equivalent to the minimum thickness at the position of the deepest thinned section. Provided that the minimum wall thickness of the thinned section exceeds the minimum code design thickness under all relevant loads (not just pressure), then it can be assumed that the equipment is fit for further service. Care is needed when calculating the code design thickness, especially in regions of equipment where there are changes of section and local loading/reinforcement requirements e.g. openings or nozzle connections, knuckle areas, saddles, stiffeners for vacuum conditions.

This approach based on minimum wall thickness is a useful screening level assessment, but can be grossly over conservative and uneconomic where thinning is localised. Both API 579 [H1] and BS 7910 [H2] provide procedures based on the averaging of spot thickness measurements made over a grid. API 579 has separate procedures for dealing with general metal loss (Section 4), local metal loss (Section 5) and pitting (Section 6). The BS 7910 Annex G procedure can cover both general and local metal loss in pipes and pressure vessels and is similar, but subtly different, to that used by API 579 for local metal loss.

The API 579 procedure is intended to assess the fitness-for-service of components where metal loss is due to local corrosion and/or erosion, or resulting from blend grinding. The local metal loss procedure can also be used to assess the fitness-for-service of generally corroded regions in certain circumstances defined within the procedure. Although these rules in BS 7910 Annex G are relatively complex compared to interaction criterion used in other procedures, they have been validated and are more comprehensive than those used in so me other procedures. The BS 7910 Annex G single defect procedure method of assessing axially aligned corroded regions generally has less inherent conservatism than API 579.

If the remaining thickness above minimum design is known, then this can be used to estimate the remaining life. A conservative estimate is then required of the rate at which corrosion or other wall thinning mechanisms will occur in future. If the actual corrosion rate is known from measurements with sufficient accuracy, then this may be used; although the possibility of the corrosion rate accelerating in future service, (e.g. through changes in process conditions), should be considered. A design corrosion rate may also be used if this can be supported by data or experience and shown to be conservative with respect to what that has occurred. You should treat all corrosion rate data with caution, and seek professional help to assess remanent life where there is uncertainty or concern.

4.2.8 Pitting

A pit is a crater on a surface brought about by corrosion. Pits can become much deeper than their diameter on the surface and eventually penetrate the wall causing a pin-hole leak, or alternatively, turn at right angles and significantly undercut the surface. Many pits (pitting) over an area can become local or general wall thinning and should be treated as such.

It is important that the form, mechanism and cause of pitting are adequately determined in order to have confidence that the assessment adequately relates to the full state of the damage. Pits can be associated with damage such as fatigue cracking, stress corrosion cracking and intergranular attack. These can strongly influence the way and rate at which the corrosion damage develops. Often the exact mechanism may not be known, and in this case it may be best to remove the pitting by grinding back to a smooth surface. It then becomes a locally or generally thinned area.

Pitting corrosion is covered in Section 6 of API 579 up to a pit diameter of the order of the plate thickness. It is recognised that when the pit diameter becomes significantly large, the region of metal loss becomes a locally thinned area and can be assessed using the local thinned area rules. Three assessment levels are applied which use the concept of the Reserve Safety Factor (RSF). Level 1 is intended to evaluate a component with pitting, subject to just internal pressure. Level 2 provides improved estimation techniques, which account for additional factors such as the orientation of pit couples with respect to the principal stress direction. Level 3 relies on numerical techniques such as finite element analysis.

A single pit or a cluster of pits can also be conservatively assessed as a planar flaw to the BS 7910 fracture assessment procedures, where the dimensions of the flaw encompass the volumetric envelope of the pitting. Representing a volumetric corrosion pit as a planar flaw is very conservative unless there are other features. It is recommended that this route is used for the assessment of pitting corrosion where brittle fracture or the presence of crack like flaws is a real possibility, or where there are gaps in knowledge of the cause or extent of the pitting.

The BS7910 fracture assessment procedures have a proven track record of giving conservative predictions of fitness-for-service for pitting in welded structures. The amount of input data required makes it more time consuming and relatively expensive to assess corroded regions compared to API 579. However, it may be that this conservatism has compensated for gaps in knowledge that would otherwise have given rise to a failure.

4.2.9 Dents And Gouges

Dents and gouges commonly occur in equipment exposed to external impacts or poor handling. A dent is a deformation of the shell of a component without any loss of wall thickness, such as a crease or inward bow. A gouge involves loss of wall thickness where the material has been scraped or cut. Dents and gouges may occur together.

The best guidance on the assessment of dents and gouges is given in API 579 [H1]. While this is specifically intended for equipment constructed to ASME codes, the methods presented may be used to assess equipment constructed to other codes providing they are appropriately interpreted. Guidance on the assessment of dents and gouges in pipelines is provided in ‘Macaw’s Pipeline Defects’ [I7]. Gouges may also be conservatively treated as crack-like defects and assessed using procedures in BS 7910 [H2].

4.2.10 Fatigue

Components subject to cycles of stress of sufficient number and magnitude will accumulate fatigue damage and eventually crack. Welds and areas of stress concentration and manufacturing deviation, such as weld-mismatch and out-of-roundness (peaking), are especially vulnerable to fatigue cracking. Consideration and assessment of fatigue need to be part of the management of all equipment containing hazardous or pressurised fluids.

Fatigue cracking in pressure vessels can be produced from pressure cycles, particularly if there are other promoting factors. Piping systems can be susceptible to thermal expansion loads, vibrations induced from flow conditions or mechanical excitation from machinery, and the effects of vibration can be amplified at small bore attachments. Non-pressure equipment that can be subject to cyclic loading are storage tanks, measuring vessels, centrifuges, pressure filters and rotating equipment, and equipment subject to pressure pulses, repeated forces from self weight and external loads/movements, impacts, and thermal shocks.

Modern pressure vessel and piping codes (e.g. BS EN 13445, BS PD 5500, ASME VIII, ASME B31.3 [B1, B2, B3, B10]) require consideration of fatigue as part of normal design. Vessels and piping may be exempt from fatigue analysis where the number of operating stress cycles is specified to be lower than a code limit (generally about 500 cycles), or where satisfactory strictly comparable experience of successful operation can be shown. Note that there is no automatic exemption from fatigue assessment for low-stress high-cycle operation.

Generally, a design fatigue analysis is necessary, which constrains equipment to operate within a limited allowable number of cycles, or within a limited loading for unrestricted cyclic use. For equipment designed to these modern codes, the original design fatigue assessment provides a good basis for specifying a design fatigue life or a period of safe duty or loading regime. For other equipment, BS 7608 [B6] gives guidance on classifying welded and unwelded features for fatigue.

The early pressure vessel design codes, AOTC and BS 1500 (first published in 1958 and withdrawn in 1984), did not require any assessment of fatigue. The issue of fatigue was first addressed in BS 1515 (1965) for design of pressure vessels for the chemical and petroleum industries. Even this approach is now considered insufficiently comprehensive to ensure that fatigue is avoided under all circumstances. Equipment in cyclic duty designed to these early codes may therefore be at risk from fatigue cracking.

Even with more modern equipment, there are a number of reasons why the level of fatigue damage and remaining fatigue life may be uncertain. This may be because:

a) A design code fatigue analysis was not carried out or is not available or was inadequate.

b) The cyclic loading operating history is uncertain or not known.

c) The cyclic loading operating history has exceeded the design criteria in respect of the number of cycles or comparable satisfactory experience that exempted the equipment from design fatigue analysis or the number of cycles allowable from the design analysis.

d) Fatigue cracking has been detected by in-service inspection.

In all of these situations, the equipment should be screened for fatigue re-assessment. This needs to take account of the number of operating cycles and the level of cyclic stress, and the hazards that would arise as a result of fatigue failure. The information given below applies particularly where there are the conditions for a fatigue failure to occur, to equipment at high hazard installations, or where a fatigue failure would have a high impact on production.

The first step of fatigue re-assessment is to thoroughly inspect the equipment at the first available opportunity to detect and characterise any fatigue cracks present. If the equipment was constructed to an older code (e.g. AOTC, BS 1500 or BS 1515), or if the code of construction is not known, then it is advised that the equipment is inspected in accordance with the manufacturing inspection criteria of BS PD 5500 [B2]. Good practice is to target the inspection on the areas most likely to sustain fatigue cracking (e.g. welds, stress concentrations, discontinuities, nozzle corners, pad reinforcements etc.) and to undertake ultrasonic volumetric inspection of the critical welds.

If no significant flaws or fatigue cracks are found, then there are two re-assessment methods that can be used, depending on the extent to which the cyclic operating history is known.

Where the cyclic loading operating history has been recorded throughout the equipment’s life, or can be conservatively estimated, a retrospective design fatigue assessment may be carried out. Where the equipment was constructed to a modern code containing fatigue design rules, then these rules can be used. Where the equipment was designed to an older code without fatigue design rules, the fatigue design rules of BS PD 5500 Annex C may be applied, providing the equipment was inspected in accordance with BS PD 5500. The cumulative fatigue usage fraction used by the previous operating history is then determined. Providing this is less than the code fatigue design limit, the equipment may continue to be operated until the usage fraction reaches the fatigue design limit.

Where the cyclic loading operating history is not known, or if it cannot be estimated with any certainty, or once the design fatigue life has been exceeded, then the remaining fatigue life should be determined assuming that a fatigue crack is present. BS 7910 Section 8 [H2] provides procedures to do this based on fatigue crack growth and fracture mechanics assessment. It is best to base the assessment on a postulated planar flaw of the largest size and most severe orientation and position that could have been missed by the inspection. Even when this fatigue life has been used, re-inspection and repeating the assessment may extend fatigue life still further providing no cracks or flaws are found.

If the inspection detects fatigue cracking or other flaws, a repair or a detailed fitness-for-service assessment is a necessity if further service is required. Again the BS 7910 Section 8 procedures may be used, but this time using the characteristics of the actual flaws that have been detected. When determining the flaw size for assessment, it is important to take the sizing accuracy of the NDT technique into account. Table 5 in Section 3.4 gives typical sizing errors for different NDT techniques.

In making re-assessments and predictions of future fatigue life, it is necessary to postulate a future cyclic loading history. Control and recording of operations is necessary to ensure the postulated history remains a conservative assumption. It is good practice to monitor any known fatigue cracks or flaws for growth at inspections of appropriate periodicity.

Process piping systems are prone to vibration-induced fatigue, but are difficult to assess in this way. Work [H12] has been done to provide a method for assessing the causes and risk of vibration fatigue so their susceptibility can be ranked for the purposes of closer monitoring. Techniques for monitoring and assessing vibration-induced fatigue in small-bore attachments are described Chapter 8 of [H13].

4.2.11 Fracture Assessment Of Crack-Like Defects

The three levels of assessment in BS 7910 [H2] and API 579 [H1] for brittle and ductile fracture are summarised in Table 10.

Table 10 The three levels of assessment in BS 7910 and API 579

	BS 7910 Section 7	API 579 Section 9
Level 1	Requires the use of a simple failure assessment diagram and fracture mechanics analysis.	Based on a maximum allowable length of defect related to the minimum design temperature.
Level 2	Generalised and material specific failure assessment diagram, similar to R6.	Uses a simple failure assessment diagram similar to BS 7910 Level 1 with refined fracture parameters.
Level 3	Allows for ductile tearing and plasticity effects through a direct computation of J.	More refined FAD similar to BS 7910 Levels 2 and 3.

The API 579 Level 1 procedure is designed as a screening tool for use by inspectors on site. The procedure uses a diagram relating the maximum allowable flaw length to the minimum design temperature of the equipment calibrated according to the reference temperature of the material. The procedure is only applicable for equipment designed to an ASME code and made from a range of ASME specified materials, since these effectively define a maximum level of reference stress and a minimum assumed fracture toughness transition curve. Different curves are given for various geometries and conditions. The most conservative assessment is for a through-thickness flaw, which can be used when the flaw height information is not available such as when only MPI or radiography data is available.

Apart from API Level 1, the API and BS procedures are all based on plotting a point on a failure assessment diagram (FAD) relating K_r, the ratio of stress intensity factor to fracture toughness, and L_r, the plastic limit load. API 579 acknowledges the use of these concepts from BS 7910 and R6 [H3]. The interaction of both fracture and plastic collapse modes of failure generates a boundary dividing regions that are potentially safe and unsafe.

The assessment of a flaw generates a single point on the FAD. If the point lies within the boundary the structure is considered potentially safe. If the point lies outside the boundary, structural failure from the flaw is possible. The use of a FAD requires computation of the K_r and L_r parameters from the stress distribution and reference solutions. Both API 579 and BS 7910 provide reference solutions for the computation of stress intensity factor and limit load for defects in flat plates and cylinders.

Fracture assessments may be particularly sensitive to variations in the input data, and experience is required to know how to deal with scatter and obtaining appropriately conservative values for use in the analysis. The possibility of brittle or unstable ductile fracture increases the consequences of inappropriate assessments. These assessments are best done by qualified engineers with suitable training and knowledge of fracture mechanics.

4.2.12 Stress Corrosion Cracking

It is very difficult to make predictions about the fitness-for-service of equipment that is in an environment where it may be susceptible to, or already contains, stress corrosion cracking (SCC). Unless there is complete confidence that stress corrosion cracking has not initiated or has arrested (for example, due to complete removal of the corrosive environment[6] etc), then SCC must be assumed and to be growing at a fast rate. For this reason stress corrosion cracking is a serious problem when it is found during service.

Guidelines for the selection of materials to avoid SCC are given in the publications of the US National Association of Corrosion Engineers (NACE) [I1]. These require a prediction of the most aggressive operating environment and for testing in that environment, or in a standard solution that is more aggressive, to determine if cracking occurs or not. However, operating environments can be difficult to predict and control in practice. The incidence of SCC in-service is often related to small levels of trace elements (e.g. chlorides in stainless steel equipment) introduced in washing cycles and becoming concentrated in crevices or by evaporation etc. Thus, even when following the NACE Guidelines suggests equipment should be free of SCC, it can and does occur in service. A list of material and environment combinations that can result in SCC can be found in [I5].

The nature of the cracking is that it is branched in nature, making it difficult to detect, characterise and size. After grinding out, it is hard to guarantee that all the cracking has been removed. These factors, combined with the potentially fast crack propagation rate of stress corrosion cracking, often mean that the only practical way to deal with SCC found during service is to replace the equipment. As this is an expensive option, it is advised that a detailed review is conducted before replacing the whole item, as there may be opportunity for selective replacement of just the affected parts. This strategy has been effectively used in a number of vessels where SCC has occurred in water jackets or limpet coils.

As an alternative to try and avoid equipment replacement, guidelines for assessment of stress corrosion cracking are given in Section 10 of BS 7910 [H2]. The crack growth rate for SCC has a sudden rise in value above a threshold value of stress intensity factor, K_{ISCC}. If the applied stress

[6] This is very difficult in practice because the corroding environment can be trapped within cracks and not flushed out by cleaning or changing the bulk environment.

intensity of an actual or postulated flaw is less than the threshold SCC value (multiplied by a safety factor, <1), then the damage may be acceptable for a period of time. This approach is difficult to apply in practice where a combination of residual, thermal, operational and externally imposed loads/stresses may be present.

Determining the value of K_{ISCC} can be difficult since it depends strongly on the test conditions, and in particular, the service environment. Because it is so case-specific there is not much K_{ISCC} data available. Where data is not available, K_{ISCC} testing under the service conditions and environment can be considered. It would be unsafe to leave a flaw characterised as being a stress corrosion crack without having adequate K_{ISCC} data.

Under fatigue and SCC, a threshold stress intensity range is the appropriate comparator. Stress corrosion cracking is included under the assessment of crack-like flaws in Section 9 of API 579 [H1] as environmental cracking. If the crack is expected to grow in service (as is the case with SCC) then the assessment must be done at level 3. The API 579 procedure is more detailed than BS 7910 with respect to assessing this kind of cracking.

4.2.13 Creep

Creep damage is manifested by the formation and growth of creep voids or cavities within the material. A commonly accepted technique for detecting creep damage is metallographic replication. This normally involves the partial dissolution of acetate replica film on to the etched surface of the material. The replica is subsequently peeled off, sputter-coated with a heavy metal, and then viewed under the microscope. ASTM standard E1351-96 [I4] gives guidance on the replication process and the interpretation of the replica. The replication method is restricted to the detection of creep damage at the outer surface.

Another approach to monitoring creep damage is physical measurement of equipment dimensions. For example, a uniform creep strain of over one percent could be easily measured using a tape measure round the girth of a horizontal pipe of say 300mm diameter, provided an accurate baseline value was known in advance, to account for tolerances on the diameter. In addition to high temperature equipment such as boilers and headers, this approach can also be applied to non-metallic materials such as high-density polyethylene tanks. BS EN 12952-4:2000 [H9] gives a method for calculating the creep damage for boilers, based on measurements of pressure and temperature.

There are no proven methods for reliably detecting the early stages of creep damage if it occurs sub-surface. Detection of the early stages of cracking by means of high resolution NDT methods such as ultrasonic time-of-flight diffraction (TOFD) is the only recourse, provided there is base line or calibration data available from unexposed material.

Creep cracking can be assessed using procedures in Section 9 of BS 7910 [H2]. Providing that other causes of cracking can be eliminated (i.e. stress corrosion cracking, fatigue or environmentally assisted cracking), the creep cracking is assessed using information about the loading (both historical and future operation), the creep crack growth rate and other material properties and the flaw size. Procedures are given for determining failure by net section rupture, crack growth or a combination of these. The influence of fatigue on the onset of ductile or brittle fracture to determine the tolerable flaw size is also considered.

Creep damage when assessed under API 579 [H1] can cover not only cracking (which must be assessed at Level 3) but also metal loss, locally thinned areas, pitting, weld misalignment and dents and gouges. Level 1 assessment is based on comparison of operating conditions to a lower bound creep regime cut-off temperature. The hardness or carbon content is also checked and a visual examination made to evaluate creep damage based on distortion or material discoloration or scaling. Level 2 assessment is used for general shell structures, and the stress components are computed using elasticity theory, either from closed form solutions or FEA. Level 3 assessment requires a detailed stress analysis and is used for cases that do not meet the requirements of Levels 1 and 2.

4.2.14 Leak-Before-Break

When damage is postulated or detected in containment equipment, it may be possible to show by calculation or experiment, that any growth or propagation of the damage would occur through the containment wall and create a stable through-wall defect and a detectable leak. This argument is known as leak-before-break. Methods to assess leak-before-break for crack-like defects are given in the flaw assessment methodologies of BS 7910 and R6 [H2, H3]. Where leakage does not give rise to an immediate safety or environmental concern and can be detected and addressed before any threat arises, demonstration of leak-before-break can provide a useful argument to support the safety of the equipment.

On its own, leak-before-break will not always be sufficient as a guarantee of safety and integrity. Leak-before-beak may not be tenable in equipment that is prone to cracking mechanisms that can produce long or contiguous multiple surface flaws (eg, erosion, SCC). Showing through-wall propagation and a stable through-wall defect requires knowledge of material properties and stresses over which there can be considerable uncertainty. Adequate methods of regular leak detection are required to limit and reveal the leakage before the through-wall flaw grows to a more dangerous size. Where leakage of fluid through a penetrating flaw is hazardous (for instance, when the fluid is high-pressure steam, highly toxic or flammable, or environmentally damaging), or where a credible leak could not be detected, the value of leak-before-break is reduced. For these reasons, leak-before-break may not be a sufficient justification for eliminating all inspection where this is reasonably practicable. Ultimately, any leakage is undesirable.

The main use of leak-before–break is within a multi-legged integrity case to cover areas where it is not possible or practicable to inspect. Some cracking mechanisms (e.g. SCC) occur randomly and rapidly. Where a crack is isolated, an analysis of the operating conditions, along with a carefully considered leak-before-break assessment, combined with appropriate inspection, can then be used to provide assurance where there is a possibility of these mechanisms occurring. It may also be used as a temporary argument to cover a set period after part-through wall damage has been detected before a full assessment can be effected. Leak-before-break has relevance for tanks and vessels that are doubly contained, providing that the outer shell is designed to withstand the pressure at its full pressure and the interspace is effectively monitored. In all these applications, the postulated leakage must be detectable and the consequences tolerable within the context of the safety case.

4.2.15 Re-rating equipment

There will be occasions when a fitness-for-service assessment indicates that damaged equipment is not fit for further service, or has a reduced life under the conditions of operation for which it was originally designed. One option at this point is to de-rate the design and operating conditions to a level at which fitness-for-service and adequate remanent life can be demonstrated. For example, this may entail reducing the maximum operating pressure, temperature, applied loads, operating cycles, or changing the chemistry of the contents. There will also be occasions where there is a requirement to increase the duty on equipment which has already sustained some damage. Again, fitness-for-service assessment can be used to assess the integrity under the proposed new duty.

When changes are made in this way, it is important to assess their effect to the system as a whole. Reduced load on one item of equipment may increase it on another. Safety valve settings may need to be reset and changes made to documents and operating instructions.

4.2.16 Possible Difficulties In Applying FFS Procedures

The main difficulties with carrying out FFS procedures are often the lack of input data for the analysis or the scatter or reliability of the data available. This can apply particularly to the material properties and the damage rate. Knowing the stresses and the past service history can also be problematic.

Often there is no fracture toughness data available for the welds or parent material from when the equipment was commissioned, and it may not be possible to obtain spare or sample material to carry out fracture toughness testing for equipment in-service. Where Charpy data is available, it is possible to estimate fracture toughness using a recognised Charpy toughness correlation. This can give very over-conservative answers and is not the preferred approach.

Obtaining the tensile properties can also be a problem, particularly if manufacturing records have been lost. These can be estimated by making hardness measurements on the relevant material and using a hardness tensile property correlation to estimate the yield and ultimate tensile strengths. If a hardness correlation is not available, or if a full stress strain curve is required, there are other instrumented indentation techniques that can be applied (see Section 4.2.5).

All NDT procedures have an intrinsic error in their ability to accurately size flaws. Certain methods can size length but not height, others are better for depth measurements, but have larger error in the lengths. For fitness-for-purpose assessments the essential inputs are the flaw dimensions and position and orientation, together with the uncertainties in these measurements. Flaw size and position uncertainty data and, in particular, the measured response versus actual flaw sizes data, is considered to be most appropriate. These are discussed for different NDT methods in Section 3.4.

With most FFS procedures it is best practice to run some sensitivity analyses to determine the effect of variations in parameters such as the flaw size, loading conditions or materials properties. This will indicate whether possible variations could result in an unsafe condition. On the basis of the sensitivity analysis, appropriate safety factors can be selected and refinements can be made to improve the reliability of the input data.

4.3 REPAIR AND MODIFICATIONS

4.3.1 Considerations For Repair And/Or Modification

It is often necessary to make repairs and/or modifications to equipment during service. The important factors to consider at the outset are the chances of achieving a satisfactory result and the life expectancy (temporary or permanent) of the repair/modification. Once these are understood, the system must be considered for re-validation (See Section 4.4.1) to determine the influence of the change to the equipment and its ability to perform its duty.

When making repairs to existing equipment, there is the potential for further damage to be introduced. This can be a result of factors such as:

- Constraints of access for fit-up/welding.
- Restraint of existing structure resulting in high residual stress.
- Presence of contamination.
- Older materials being more difficult to weld than current materials.
- Restrictions on preheat.
- Uncontrolled cooling rates.
- Constraints on post weld heat treatment.
- Potentially poor surface finish.
- Creation of stress-raisers
- Dimensional tolerances and alignment after repair.
- Material compatibility.
- Balance in rotating equipment.

These factors may be difficult to assess and expert assistance is strongly advised to ensure that safe repairs are made. There can also be a financial benefit from this advice. In many cases experience has shown that expert assistance has optimised the repair process, reduced the risks of failure (or defects) at inspection, and minimised the time taken for the repair.

It is good practice to use an approved Design Specification to ensure the repair method is suitable. In cases where the Specification is no longer applied, then a modern ‘equivalent’ design can be used. This will frequently require some professional judgement to ensure it is appropriate for the duty. This helps avoid both over and under specification.

Examples of particular areas of concern in these cases are:

- Classification of flanges.
- Use of appropriate weld configurations.
- Accurate data on defect size or orientation for fitness-for-service review.
- Accurate thickness data for pressure rating.
- Use of actual material property data to reduce conservatism from specifications.

4.3.2 De-rating As An Alternative To Repair

A repair is not necessarily the most cost effective method of dealing with damage to equipment. Consideration can also be given to the possibility of making fitness-for-service and operating assessments to justify changes to the operating conditions of the equipment, which would then preclude the need for any repair or replacement.

This approach can be used in circumstances where a temporary solution is required. For example, where general thinning is experienced in a vessel, using shell plate thickness calculations, the thinning may be unacceptable at the stated safe operating limit, whereas it may be considered acceptable at a lower pressure. Section 4.2.15 considers de-rating on grounds of fitness-for-service.

4.3.3 Reasons For Making Repairs

It is important to understand the reasons for making repairs. Firstly to prevent recurrence of the original cause, and secondly to ensure the repair will be resistant and will not introduce any further damage. Evaluation of these factors can make a contribution to improvement in reliability and reduction in costs, as well as complying with legislation.

4.3.4 Specifying A Repair

The general principle in specifying a repair or modification is to ensure that there is nothing that gives rise to danger, or otherwise impairs the operation of any protective device or facility for inspection. For pressure systems, PSSR 2000 [A3] places these responsibilities on the *employer* of the person carrying out that repair or modification. You can apply these principles for repairs/modifications to other types of equipment containing hazardous fluids.

Employers of those making temporary or permanent repairs to equipment containing pressure or hazardous fluids are advised to take account of the following aspects before work begins:

- The original design specification.
- The duty for which the system will be used post repair.
- The effects the repair may have on the integrity of the system.
- Whether the protective devices remain adequate.
- Whether the written scheme of examination remains suitable.
- Whether repair welding on live plant would create a hazard, e.g. hot tapping [D4, D5].

Where substantial repairs are to be made, the Competent Person (for pressure systems) or other independent adviser should be consulted before the work begins. Companies are also recommended to consider the impact on the business operation and reputation in the event of further problems.

At the commencement of any repair or modification it is important to determine the technical and regulatory requirements of the design and fabrication in relation to the risk. These can be simple or complex depending on the type of equipment. While technical requirements for repairs and modifications to pressure systems are often well understood, those for equipment in ‘hazardous systems’ that are covered by other regulations, for example COMAH, IPPC and PUWER [A4, A9, A6], may need to determined on a case-by-case basis.

Typical technical requirements are:

- Repairs/modifications should be designed and fabricated to ensure the equipment complies with appropriate code requirements. These may be the original code or a suitable current specification.
- Adequate allowance must be made for the inspection of the repair/modification.
- Mitigation measures may be required where the repair/modification is considered to introduce a higher level of risk. For instance, rotating equipment may need to be designed to protect against

high-energy failures, or storage tanks or pipelines may need protection to guard against potential large containment losses.

Once the technical requirements are clear, then the following constraints on the repair operation should be considered.

- The material of construction.
- Suitability for fabrication and/or welding.
- Location and access limitations.
- Welding requirements and heat treatment.
- Ability to inspect the final result.
- Post repair cleaning and/or risk of contamination.

Assistance from a Materials Engineer at this stage can help the process to achieve the technical requirements, and lead to efficient and cost effective implementation.

4.3.5 Removal Of Flaws

When surface and near surface flaws are found, the most common alternative to fitness-for-service assessment is to remove the flawed material by grinding. Grinding out a flaw is a straightforward solution, but it is important to grind out sufficient material to ensure that the entire flaw has been removed, as a small remnant of a flaw could initiate further damage. After any grinding you should determine whether the wall thickness remaining is adequate.

Grinding is a skilled operation and appropriate training is needed to ensure that operators can machine a smooth profile groove. Care must be taken to avoid machining in sharp features, which may provide sites for initiating fracture, fatigue or corrosion, and to avoid smearing the surface, which can mask a defect. Incorrect grinding can introduce residual stresses and/or regions of high surface hardness. Confirmation that a flaw has been removed requires a surface NDT method such as magnetic particle inspection (MPI) or dye penetrant inspection.

If the material remaining after grinding a smooth profile groove is greater than the minimum design thickness for the part, no further action may be necessary other than to reinstate any surface coating. When a flaw is ground out to a depth resulting in a wall thickness below the minimum design thickness, the region may be treatable as a locally thinned area (see Section 4.2.5). Fitness-for-service assessment procedures (e.g. BS 7910 or API 579 [H2, H1]) can then be used to justify whether the remaining thickness is adequate for further service.

A weld repair to reinstate removed material is an option if the remaining wall thickness after grinding is not adequate, or simply to restore the thickness to the design condition. This can be become costly since qualification of the repair weld procedure and the welder would normally be required, and it also has the risk of introducing further flaws. When making a weld repair, care must be taken with the welding parameters to avoid excessive HAZ hardness, since often PWHT is not possible. Specialist techniques are available (such as the temper bead technique) to carefully control the repair weld heat input and to offset the disadvantages of a lack of PWHT.

Sometimes it is best to cut out completely the area containing the damage. Care must be taken that the machining does not produce excessive heat, flaws or residual stresses. The opening can then be covered with a patch plate or blanked nozzle, suitably designed to ensure the opening is adequately reinforced.

4.3.6 Repair Methods For Temporary Or Permanent Repairs

(a) Temporary repairs

Leakage from damaged pipes and other equipment can be prevented or sealed using proprietary composite plugs, overwraps, clips, clamps etc. The products available range from wraps and bands to clamps and pressure containing boxes, some capable of carrying axial load. Where pipe sections are removed, mechanical connectors are available to link the ends.

All these repairs should be considered temporary, unless a technical review has determined the repair is safe to make permanent. The period in which a repair may be left in place will depend on circumstances, experience and, where appropriate, agreement between the Duty Holder and the Inspecting Authority[7]. In special cases, repairs may be in place for several years. Whenever temporary repairs or modifications are made, it is important to document the work carried out, future inspection requirements, and the period in which the repair/modification may remain in service.

It is important to monitor the evolution of the damage to the equipment under the repair and deterioration of the repair materials. While current NDT techniques are limited in this respect, it may be necessary to remove and reinstate the repair. A process to identify vulnerable repairs and to assess and monitor their condition in order to prevent secondary failure is strongly advised.

The Health and Safety Executive has issued a Safety Notice relating to weldless repair of safety critical piping systems [D6]. Guidelines on the applicability of these pipe repair techniques are available in HSE Offshore Technology Report 2001/38 [D7]. A draft ISO Technical Specification is available covering composite repairs to pipework [D8]. Further references may be found in Section 1.5.2.

(b) Permanent (welded) repairs

Permanent repairs/modifications introduce new parts and welds, and can change the original design intent of an item. In order to plan and perform these, appropriately qualified and experienced personnel are essential. Where welding is concerned, the key factors are:

- Development of the welding procedure.
- Welding positions and access restrictions (fixed equipment).
- Weld metal type.
- Weld preparation and profile.
- Influence on parent material in the heat affected zone.
- Application of purge gases.
- Qualification of the procedure and the welder for the repair situation.
- Access and ventilation (particularly confined spaces).
- Influence of weather conditions.
- Location (e.g. working at height, hazard to live equipment).
- Cleanliness of equipment/weld preparation.
- Minimisation of residual stresses and need for PWHT.

[7] Temporary repairs are often a source of trouble, they may very easily become permanent even if not suitable for long term service. There is also a risk that such repairs are done in a hurry, without full assessment of implications.

Within the scope of the repair, additional work may be needed to overcome changes that have occurred to the material while it has been in-service to improve weld reliability. Typically this may be pre-heating, hydrogen diffusion (bake-out) treatment, or weld overlay.

Weld repairs to older equipment have a greater potential to contain a range of defects. Different NDT techniques and procedures from those applied when the item was new may be needed to overcome, for example, the limits of access or to accommodate a change of weld design or arrangement of fillet or butt welds. Older steels (containing high levels of sulphur and phosphorous) are more susceptible to lamellar tearing when stressed in the though-thickness direction, such as when attachments are fillet welded to plate. As a component ages, deteriorates and is repeatedly repaired, the judgement for continued service and monitored service life may require a more thorough mapping of defects and their size.

4.3.7 Revalidation After Repairs

After temporary or permanent repairs are made, it is good practice to revalidate the equipment to ensure that the repairs have been carried out as specified and have not had any detrimental effect on integrity (see Case Study 12). Revalidation also needs to consider any effect of the repairs on the equipment or system as a whole. For example, repairs might necessitate a change to the operating regime or to the written scheme of examination, or the introduction of monitoring. These aspects are dealt with in the next Section.

4.4 REVALIDATION OF EQUIPMENT

4.4.1 General Considerations

At the time of manufacture, pressure equipment normally has a validated design for a prescribed set of defined operating conditions. On the other hand, non–pressure equipment, as used for the containment of chemicals (e.g. storage tanks, hold vessels, mixers etc.) may be in service with very limited documentation of design conditions or defined operating limits. Changes to the operating regimes of both these types of equipment, or to their physical structure, commonly occur over the many years that equipment is in service.

Changes to operating regimes may involve:

- Changes in temperature.
- Changes in pressure.
- Changes in flow rates.
- Modification of process chemistry/environment.
- Modification to product density.
- Changes to system loading (e.g. pipe re-routing/hangers etc.).

Any of these may result in conditions outside the original design envelope or the conditions under which satisfactory operations have been demonstrated. For mechanical equipment (e.g. pumps, centrifuges etc.) there may be other factors, for example, the speed of operation or the load carried. In addition, changes to drives, coupling, available spares or lubricants may alter dynamic loads, and ultimately affect integrity.

These changes may be considered as step changes imposed on equipment through the operating regime. There is real experience that subtle incremental changes to operating conditions can progressively also move an operating regime outside design conditions. This has been shown to happen with both pressure equipment and other types. In addition to these, changes occur to the physical structure of the equipment itself through repairs and modifications and deterioration. In all these cases, the equipment needs to be revalidated.

There are opportunities to review the adequacy of the design of the equipment at various stages during its service life. This is well established when carrying out formal ‘risk based’ or ‘criticality reviews’ that are driven by a particular objective, for example, shut down optimisation and planning. These opportunities apply mainly to pressure equipment. For other types of equipment, it is more likely that these items are not reviewed for changes, as there is often no formal requirement to do so.

It is always good practice to revalidate the design adequacy of equipment whenever such changes occur for all types of equipment, and to make such reviews on a regular basis. It can be a formal process for equipment within pressure systems when the approval of the Competent Person is required.

Key points for consideration in the re-validation process for different changes are highlighted in the following Sections. The spider chart below illustrates some of the aspects that may be needed for revalidation.

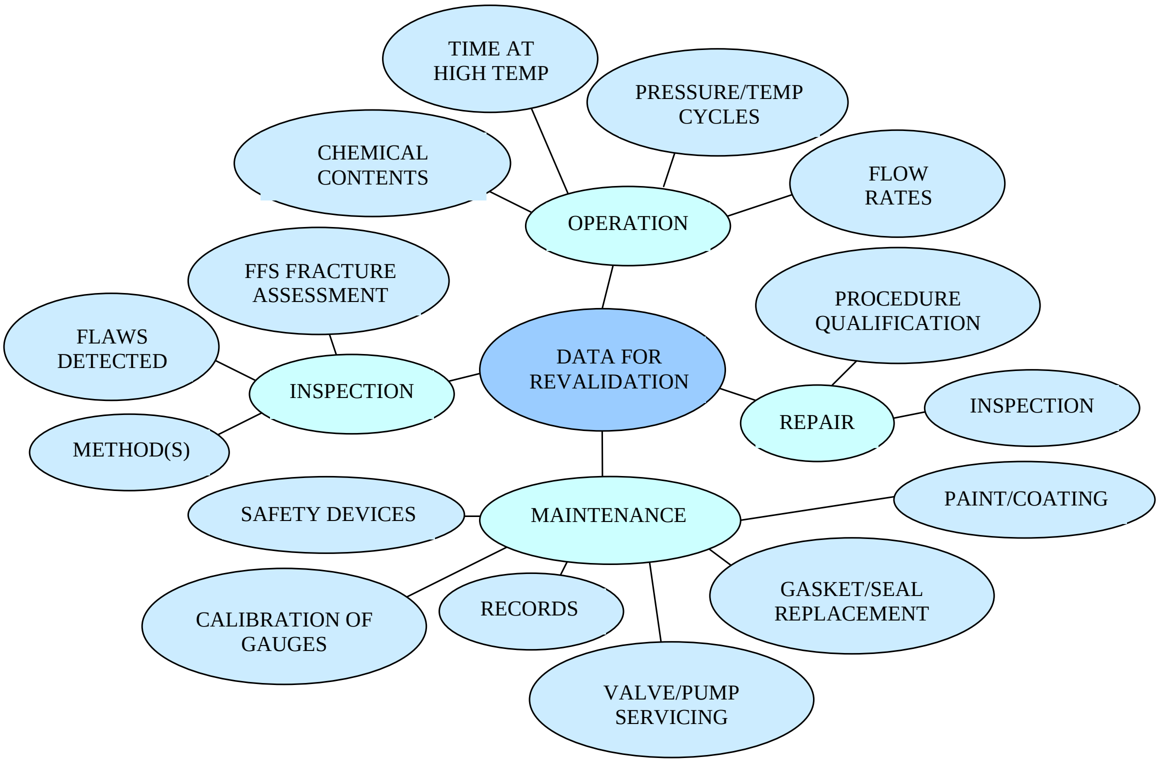

Figure 8.Some of the key aspects for consideration during revalidation of equipment

4.4.2 After Physical Modification And/Or Repair

The design of modifications to equipment should normally be carried out to comply with the original design code. Fabrication procedures, on the other hand, are best done to the standards of the equivalent modern code. In addition to considering the requirements of these codes on the design, there are likely to be other factors to take into account.

- The access and geometry of the equipment may limit or change the type of welding process that is possible from that originally used. This can affect the quality of the finished welds.
- Pre-heat and post weld heat treatment may be impossible or limited, leading to different properties in the finished weld to those achieved during first manufacture.
- Materials used for the construction of modifications/repairs may vary from the original specification, due to evolution of steel making practices and availability. For, example, stainless steel is available in standard and low carbon grades, but may be dual certified. Low carbon grades would not be appropriate for high temperature service.
- It may not be possible to conduct NDT to the same technique, procedure or standard as the original code (e.g. due to access limitations)

Even though the modification/repair may comply with the design codes, consideration is needed of the effect of the change on structural integrity, and on flow and temperature distributions (see Case Study 13). For example, fitting a branch to repair a corroded shell may adversely alter flow patterns within the equipment, whereas a weld overlay would not. Weld overlays are not currently covered within pressure vessel design codes, but are a useful repair method when carefully applied.

Following modifications or repairs, a reference to the changes should be made in the equipment records system or the maintenance log (see Case Study 14). The records should contain as relevant:

- A reference number and drawing of the completed modification/repair.
- The design code and construction category used.
- Design loads (including local, cyclic, dead and imposed, dynamic and wind loading).
- The calculated design stress, minimum thickness, corrosion allowance.
- Pressure-temperature combinations for which the modification/ repair are suitable.
- Materials of construction including supports, attachments and gaskets.
- Heat treatment charts.
- NDT reports.
- Quality assurance documents (e.g. welder approvals, weld procedures etc.).

4.4.3 Changes In Design Codes

There is normally no reason to re-validate equipment as a result of changes to design codes. There are, however, some situations where revalidation of equipment should be considered, often as a result of industry experience or legislative change. Typical examples are:

- Modification of the Nelson Curves for steels in hydrogen service.
- Change in gasket materials.
- Equipment in critical applications designed to early codes without the requirement for fatigue analysis may need to be revalidated for fatigue. Further information is given in Section 4.2.10.
- Notification of the causes of major failures.

If you are uncertain as to the impact of changes in design codes or industry experience on your equipment, then it is advisable to seek specialist support.

4.4.4 Change In Operating Conditions

It is often necessary to operate existing equipment under new operating conditions. For example, this could be operating cryogenic vessels at a lower temperature than the original design temperature, operating high temperature plant at an even higher temperature. Using storage equipment for containment of different substances may mean that a different chemical or corrosive environment will be experienced, or a different hydrostatic head developed.

When equipment changes its service conditions, you should regard it as having a higher risk of damage until service experience or assessment shows otherwise. Damage from previous service may increase at an accelerating rate under the new conditions. The reason(s) for changing the service conditions should be taken into account when considering the risk.

4.4.5 Assessment For Low Temperature Conditions (Generally Below $0^{o}C$)

Ferritic steels show a transition from ductile to brittle behaviour as the temperature drops or the thickness increases. A material that may be ductile and show adequate toughness at one temperature could show a significantly lower toughness and brittle behaviour at a lower temperature. This is why it is important, when fabricating from ferritic steels, to carry out impact or fracture toughness testing or at or below the lowest anticipated service temperature. Materials such as austenitic stainless steel or aluminium, do not show this transition behaviour and generally maintain their toughness at low temperature.

Revalidation for low temperature conditions could be due to a proposed change in operating conditions to lower temperatures. However, it can also be necessary to re-assess existing conditions in the light of transient low temperature events that had not been considered in design, such as during depressurisation. Equipment designed to older design codes may not have impacted tested material or allowed for these types of transient conditions.

Auto-refrigeration can occur as a result of a leak from a joint, or a blow-down event, or when there is a sudden loss of containment. The reduction in temperature is associated with the rapid reduction in pressure. For example, auto-refrigeration can occur when gases (such as hydrocarbon gases, chlorine and ammonia), stored under compression at ambient temperature are depressurised quickly, and cool due to adiabatic expansion.

Design codes, such as BS PD 5500 [B2], have special provisions for equipment intended to operate at low temperature (normally taken to be below 0^oC). Materials are required to achieve satisfactory impact values at a test temperature relating the minimum design temperature, the thickness, stress, construction category and state of post weld heat treatment. Equipment operating at or near low temperatures requires revalidation to proposed changes to operation involving a reduction to the minimum design temperature, an increase in thickness, an increase in stress, or any combination.

The HSE publication on the Assessment of Pressure Vessels Operating at Low Temperature (HSG93) [H11] provides three assessment routes for revalidating equipment for low temperature operation. All routes require knowledge of the operating conditions, including transient conditions, and full inspection of the vessel showing the vessel to be free of significant flaws. It is assumed that a Competent Person makes the assessment.

Routes 1 and 2 are based on assessing the vessel against the design code. If the vessel has been designed for low temperature operation (i.e. original impact values are available), then Route 1 recommends that any change is assessed to the original code, or to the latest issue of the recognised national standard. Route 2 applies if the vessel was not designed for low temperature operation (i.e. original impact values are not available), but impact values can be established. Where there are insufficient impact property data available for the materials, BS PD 5500 Appendix D may be used to assess vessels employing the permitted assumption that normal pressure vessel steels attain a satisfactory impact value at 20^oC. Route 3 is a fracture mechanics fitness-for-purpose assessment that can be followed when the Charpy toughness is in doubt or significant defects found.

Thus, when considering any proposed change, it is therefore first necessary to determine whether this would mean that the equipment would be operating outside the limits of the original design code (e.g. BS PD 5500). There may have been a margin between the original service temperature and the lowest permissible temperature. If the equipment is not already operating at lowest temperature, the change may be justifiable using existing material property data.

If the change takes the equipment outside the limits of original code, then it may be possible to re-validate the equipment to the code by carrying out further Charpy testing at a lower temperature. Of course, with older equipment, there is unlikely to be much spare material. Taking boat samples from a shell is a possible method of obtaining material for Charpy testing, but this method may require a subsequent repair of the sample location.

If it is not possible to undertake further Charpy tests, it can be possible to estimate the Charpy energy from original tests at a higher temperature. If no original Charpy test data is available for the equipment, it may be possible to use minimum values given in material specifications. Extreme caution should be exercised when using idealised or estimated Charpy transition curves, since they cannot be relied upon to always make conservative predictions.

If it is not possible to justify the change to the original code, or to carry out further Charpy testing, then a fracture mechanics approach can be used, such as BS 7910 (see Section 4.2). Ideally, fracture mechanics testing would be carried out. In some circumstances, the fracture toughness of the material can be correlated from Charpy data. This method normally estimates a very conservative value of fracture toughness.

The fitness-for-service approach requires a flaw size to be assumed. This is likely to be the largest flaw that could still be present after inspection based on fabrication code-allowable flaw sizes, or the NDT sensitivity level and flaw sizing error. This can be used to determine the maximum operating pressure based on the toughness at the lower temperature. The approach can also be used to justify operating at a higher pressure at the same temperature.

A similar published procedure addressing change of service temperature is found in Section 3 of API RP 579 [H1]. This covers the assessment of existing carbon and low alloy steel pressure vessels, piping and storage tanks for brittle fracture and can be applied to continued service or change of service.

Specialist support is strongly recommended due to the complexity and difficulty of setting limits in these cases.

4.4.6 Increase In The Operating Temperature

When a change is proposed to equipment that would increase its maximum operating temperature it is necessary to revalidate with respect to its strength and susceptibility to creep. If inspection has shown that the equipment is free from significant defects, and a good measurement of the current wall thickness is available, then it is appropriate to revalidate the equipment for the increased temperature according to the original code of construction. It must also be considered that a higher temperature may take the equipment into a region susceptible to SCC or hydrogen attack (see Section 4.2.12).

Codes such as BS 1500, BS 1515, BS PD 5500 [B2] and ASME VIII [B3] provide tables of allowable design stress for standard specifications of materials at temperatures under the creep regime. An assessment of the adequacy of the current wall thickness of the relevant parts (making appropriate allowance for any predicted loss in thickness during the remaining life of the equipment) relative to the minimum required wall thickness calculated the code formulae would be all that is needed.

Where a design stress at the relevant temperature is not available or insufficient, then it is possible to use a value derived from tensile testing of actual parent and weld material. If original material is not available, there are methods to remove small samples of material from lower stressed areas from which miniature tensile specimens can be obtained. Alternatively, it is also possible to use correlations to extrapolate the tensile properties to higher temperatures.

Where the increase in temperature would take the material into a regime where creep effects could be significant, a more detailed consideration is needed. This would require a rigorous review of the materials and standard of the equipment's original construction and its current condition, the suitability of the material for creep service, and an assessment of creep life. Such considerations are beyond the scope of this report.

4.4.7 Changes To Pressure And Applied Loads

Revalidation of the design is required when a proposal is made to increase the loading on equipment beyond the design condition. The proposed change may be an increase in design pressure, self-weight or contents, or additional forces and moments imposed by changes to attached piping and supports or operating temperatures. If inspection has shown that the equipment is free from significant defects, and a good measurement of the current wall thickness is available, then it is appropriate to revalidate the equipment according to the original code of construction.

Revalidation should assess the adequacy of the existing wall thickness (making appropriate allowance for any further loss in thickness during the remaining life of the equipment) by calculation of the minimum required wall thickness under the new loading. Where design pressure has increased, a new hydrostatic test may be appropriate. The effect of increasing the pressure in a single vessel on other parts of the system also needs to be considered.

Any change in pressure (increase or decrease) needs to be accompanied by changes to the settings of safety valves and other protective systems.

4.4.8 Changing Contents And Environment

Revalidation of equipment is required when a change to the fluid or the environment (internal or external) is proposed. The continued suitability of the materials and welds must be reviewed. Materials selected with one purpose in mind may not be suited to another. For example, petrochemical equipment procured with sweet oil service in mind may not be suitable for sour feed. A stainless steel vessel intended for inland use may not be suitable in a coastal environment. A relaxation of water chemistry controls on boiler systems may expose systems designed for certain specified water chemistry to attack.

Changes to the fluid and environment may affect the corrosion allowance within the design and the anticipated design life; it may necessitate shorter inspection intervals until favourable experience has been obtained. Changing contents to more hazardous substances may affect the risk assessment and the commensurate integrity measures. If there is insufficient in-house expertise, then it is prudent to employ a qualified materials engineer to undertake the review.

4.4.9 Changing Operational Mode

Changes to operating mode could include higher cyclic loads, thermal shock, different flow conditions, valve closure times, depressurisation times etc. Where these changes lie outside the design basis and existing experience, revalidation of the equipment is required. Depending on circumstances, the revalidation could involve a reassessment of the fatigue life, or the effect of peak pressures and/or minimum temperatures in the system, or local yielding.

4.4.10 Revalidation Of Second Hand Equipment, Reuse, And Equipment From Storage

From time to time a user of plant may wish to purchase and use second hand equipment or to use equipment taken from storage or another duty. All of these should be undertaken with extreme caution, especially if the original design and manufacturing records are not available. Most equipment is designed and manufactured with a certain use in mind, and changes to that use may not lie within the original design intent.

It is important to establish the known life of the equipment and to identify any gaps in service history and potential ageing damage. Equipment that has been bought second-hand may not have previous service records. The availability of such records ought to be a consideration when purchasing second hand equipment.

Before further service, a thorough and detailed inspection is needed to determine the current condition and any damage during previous use or storage. Sometimes welding onto old or contaminated steel may be necessary before the equipment can be put back into service, and care must be taken. Design analysis and re-verification is needed where the proposed use lies outside the original design basis or when there is damage from previous service. From this, new safe operating limits and design life can established and recorded on a new plate and documentation on the equipment

4.4.11 Responding To Industry Experience

From time to time, new industry experience is gained. This may be as a result of publicised failures or from research and development. Sometimes there is a spate of failures (e.g. shell boilers in the

1980's), major incidents (e.g. see HSE report of incidents at BP Grangemouth [E4]), or new insights (e.g. the PANI inspection trials [G1]) and understanding (e.g. effect of sour environments).

Experience is disseminated in a variety of ways. These can include HSE Safety Notices and site visits, industry trade bodies (e.g. SAFed and EEMUA), Competent Persons, professional institute seminars (e.g. IMechE, IChemE, The Welding Institute), journals and other publications (e.g. Engineering Failure Analysis). Duty Holders are expected to maintain their awareness through these and other means, and take appropriate action to safeguard their equipment when necessary. Organisations are encouraged to keep up to date with current practises and codes, and to participate in research, development and information sharing via organisations such as:

- Institution of Mechanical Engineers (Pressure Systems Group and Process Industries Division)
- Institution of Chemical Engineers.
- Institution of Plant Engineers.
- British Institute for NDT.
- The Welding Institute.
- Institute of Materials, Minerals and Mining.
- The Energy Institute.
- Engineering Equipment and Materials Users' Association.
- Safety Assessment Federation.
- Health and Safety Executive.
- UK Offshore Operators Association etc.

Useful references and websites are given in Section 1.5.

4.5 REVIEW OF SCHEMES OF EXAMINATION AND CONDITION MONITORING

4.5.1 When To Review The Scheme

Schemes of examination for equipment containing hazardous or pressurised fluids need to be suitable to address the risks from damage in all circumstances, and therefore need regular review, particularly as equipment ages. The Duty Holder for the equipment should therefore ensure that the scheme is reviewed by a competent person (Competent Person) on a regular basis throughout the lifetime of the plant. For pressure systems, this is a requirement by law under PSSR 2000 [A3].

It is a good practice to review the whole scheme of examination following each thorough inspection. This enables the results of the inspection of particular items of equipment to be considered as part of the review process of the whole scheme. Damage detected in one location may increase the possibility of it being present elsewhere. A change to the interval to the next inspection of one item may be appropriate for other equipment. For pressure systems, the Competent Person carrying out the examination of the pressure system is required to state on the report of examination whether the existing scheme of examination remains suitable or should be modified, and to modify the scheme if this is recommended.

Beyond this, there is no general rule on how frequently to review the examination scheme, nor the scope and extent of the review process. It is generally accepted good practice, however, that the schemes of examination need to be reviewed more regularly as the system becomes older, even when an examination is not scheduled. Review of the scheme is normally necessary when damage is detected or repairs and modifications carried out.

It would be expected that the Competent Person, in deciding whether to carry out a review, would adopt a ‘risk-based approach’ and take into account those relevant indicators that may provide evidence that the system could be deteriorating. The Competent Person will take account of factors that could lead to a modification to the nature, extent or frequency of examination, such as recognition of a previously unsuspected potential mechanism, or a change in the operating conditions or contents of the system.

This process of review and amendment of the scheme of examination is an integral part of risk-based inspection. Further information can be gained from HSE Contract Research Report 363/2001 ‘Best practice for risk based inspection as a part of plant integrity management’ [F3]. This same principles apply to both pressure systems and non-PSSR equipment.

4.5.2 Extent Of Examination

As equipment becomes older and the ageing process progresses, it would be expected that a greater extent of the equipment would be examined. The examination would be extended to include those areas of the equipment that have been identified as being most at risk of ageing. Where damage or degradation has been detected in one location, extension of the inspection extent to cover all similar locations would be appropriate.

4.5.3 Nature Of Examination

As the inspection and operational experience of the pressure system develops, then some modification of the nature of the examination would be expected to complement the results being obtained. This may involve changes in the NDT techniques and procedures to be employed to detect the potential or actual damage mechanisms identified, and the use of more quantitative techniques, such as time of flight diffraction, to measure the damage. The use of diverse techniques and repeat inspection using multiple NDT operators are considerations if higher inspection reliability is required.

4.5.4 Frequency Of Examination

As the ageing process progresses and accelerates, it would be expected that the periodicity between examinations would decrease to reflect the increase and uncertainty in the damage rate. This will provide forewarning of an impending unsafe situation or failure and allow time for planning replacement equipment. This is not always the case though, and in some circumstances the act of inspection will disturb the operating conditions, such as cooling equipment down, removing or disrupting protective scales or allowing air and/or moisture ingress. These can result in more aggressive conditions, and can increase the rate of degradation (see Case Study 8). Condensation that occurs during shutdown in equipment that normally operates under dry service conditions can result in various corrosion conditions when service resumes. Another example is de-aerator cracking when the cool down prior to inspection causes mechanical cracking of the internal scale and subsequently localised corrosion occurs at the exposed sites.

Sometimes an item of equipment consists of more than one discrete component (i.e. a water tube boiler comprising of a steam drum, mud drum and numerous headers etc.). It may be that, over time, the examination periodicity of the different components is varied as they age and deteriorate at different rates. This can make the management of these assets quite complex. Great care is needed to ensure that the scheme of examination is properly applied.

4.5.5 Condition Monitoring

Several approaches to condition monitoring exist. These include:

- Periodic re-examination of known defects at a particular location.
- Periodic re-examination of the whole component.
- Continuous monitoring of defects/specific locations during service.

For each of these approaches, selection of the most appropriate NDT technique is very important. The following aspects need to be considered:

- Flaw detection capability and flaw sizing accuracy for fitness-for-service assessment.
- Reproducibility/compatibility of the technique.

If the rate of ageing is to be determined accurately from condition monitoring, it is essential that the same set-up parameters are used from examination-to-examination. For corrosion mapping and time-of-flight-diffraction, for example, the key set-up parameters are:

- Flaw detector.
- Probe types.
- Probe separation (TOFD only).
- Couplant.
- Equipment calibrations, including test gain/recording level and datum.

When monitoring corrosion damage manually it is vital that the measurements at each examination are carried out at exactly the same position on the component. To facilitate this, it is good practice to make a permanent mark on the component. Where the component is curved (e.g. a small diameter pipe), it may be necessary to machine a ‘flat’ on the component to prevent probe ‘rock’ which can introduce unwanted errors in measurement.

It may be advantageous or necessary to select an NDT technique that differs significantly from the technique used for the previous examination. Then it is important to ensure that the results generated are compatible with those from the previous examination if a comparison is to be made. Otherwise it may be very difficult to determine (with good accuracy) the change in damage that has occurred during the inspection interval. There is often the temptation (for good technical and/or commercial reasons) to change inspection technology during the life of the equipment without full consideration of the implications.

In addition to NDT techniques, there is a range of other methods that can be used for monitoring the condition of process equipment. These may be divided into continuous methods and sampling methods. Examples are given in the Table 11 below.

Table 11 Examples of continuous and sample monitoring

Continuous monitoring	Monitoring by sampling
Vibration measurement	Vibration measurement
Temperature measurement	Temperature measurement
Flow measurement	Flow measurement
Fluid level measurement	Fluid level measurement
Product quality	Oil condition
Density	Coupon corrosion
Dust loading	Non-invasive inspection
Shaft position	Visual inspection
	Dimensional checks for wear
	Creep replication
	Alignment

4.6 FINANCIAL CRITERIA FOR DETERMINING THE END OF EQUIPMENT LIFE

4.6.1 Which Criteria To Consider

In recent years, increased competition within industry has driven the need for optimising the cost of plant inspection and maintenance and repairs (IMR) and the decision of when best to replace equipment. Commercial software tools for financial analysis have been developed to address this need and to predict the optimum IMR and replacement strategy. These are of particular interest to the oil and gas and power generation industries where fully quantitative financially based plant optimisation methods have a variety of applications.

Financial assessments of costs need to take account of the possibility that equipment will fail. Unplanned or forced shutdowns have financial consequences in terms of lost production, while explosions, fires and releases can cause major plant damage, casualties and off-site consequences that can significantly damage a company's liability, reputation and sales. Prudent replacement of equipment can improve reliability and reduce the risk of failure, and, if undertaken at the right level and time, can bring about considerable cost savings.

The basic principles underlying methods of cost-risk optimisation of the replacement decision are reasonably straightforward. The optimisation is of minimising the total service cost over the equipment lifetime. Excluding initial purchase and direct operating costs, the main costs that have to be considered are:

(a) The costs of inspection, maintenance and repairs.

(b) The expected value of the cost consequences of failure.

(c) The cost of replacement.

If there is just one failure mechanism giving rise to one set of financial consequences, the expected value of the cost consequences of failure is simply the product of the probability of failure and the cost of the consequences. Of course, there can be many types and forms of failure and each will have a set of consequences. In this case the cumulative costs of failure at a given time is the summation of the expected values of each failure–consequence scenario.

Without adequate IMR, the failure probability will undoubtedly increase as ageing and wear-out take place. Good practice is to invest sufficiently in IMR so as to keep this probability under control. The costs of running equipment therefore usually rise at an increasing rate.

4.6.2 When Is The Best Time To Replace?

If the equipment is to be replaced, when is the best time to do it? This is the time when the total business costs of providing and safely maintaining the asset or service are minimised over a defined period. It is intuitive that with continuously increasing business costs over time, the costs in the first half of life are always less than in the second half. Therefore, if the equipment is to be replaced once, and the costs of the replacement are the same as the original, then the best time is half way through the required period of service.

Is a single replacement at this optimum time cost effective compared with running the original equipment through to the required period of service? This depends on the replacement cost. A comparison of the total service cost with and without replacement at the optimum time will provide an answer. Even with one replacement, the total service life cost may be unacceptably high, particularly if the risks of failure are high. In this case the possibility of replacing the equipment more than once should be considered.

The analysis implies a number of simplifying assumptions. It assumes that the value of money remains constant and that there is no interest on money not spent. In practice neither of these assumptions is true. These correction factors can be allowed for by methods such as discounted cash flow and compound interest analysis. While these are in the domain of accountants, they do not alter the underlying principle of the approach.

Obtaining the probability of failure for an item of equipment over time is not generally straightforward. If historical data of the time to failure is available for the item under similar conditions, then this may be used. It is also possible to use expert elicitation. These methods are ideally suited for obtaining inexpensive preliminary engineering insights, and to identify any need for more quantitative analysis.

Generally, for single items of equipment, it is necessary to establish a particular damage mechanism along with a failure criterion and then to formulate a damage propagation model with statistically distributed engineering inputs. For example, the damage mechanism could be corrosion and the failure criterion could be plastic collapse or through wall penetration. In this case the input distributions could be the corrosion rate and the tensile properties.

Often the difficulty in this sort of planning is knowing how long a service life to assume. This will depend on many factors outside the integrity of the equipment itself. The evolution of feed stock, installations, products, markets and the supply chain are typical factors that may influence the required service life. Asset management of the equipment therefore needs to be part of the overall business planning process.

APPENDIX 1. PROCESS MAP AND AUDIT TOOL

Process Map for the Management of Equipment Ageing

Integrity awareness and culture (Section 1)

- What pressure systems and/or containers of hazardous fluid are on site?
- Who is responsible for this equipment?
- What consideration is given to equipment ageing and life extension?

↓

Management of ageing assets (Section 2)

- What company strategies or policies are in place for managing ageing?
- What records/documentation about the equipment are maintained?
- Can your company demonstrate it has the competencies required?
- What provisions are in place for the retention and use of corporate knowledge?

↓

Identification and control of ageing (Section 3)

- Does the plant/equipment have a retirement date?
- How well is the equipment lifecycle known?
- How aware is your company of the indicators of ageing?
- Does the approach to inspection take account of the stage of equipment life?

↓

Addressing ageing through assessment and remediation (Section 4)

- What options are considered when ageing related damage is detected?
- How is fitness-for-service assessed for aged components and components where the remanent life is uncertain?
- What procedures are used in the event that equipment requires repair?
- What procedures are in place regarding revalidation of equipment?
- Do written schemes of examination reflect the equipment's age and condition?
- What policies are in place for determining the end of equipment life?

1 Integrity awareness and culture

1.1 What pressure systems and/or containers of hazardous fluids are on site?

As a person with responsibility for equipment containing hazardous fluids and/or pressure, you are expected to know what and where containers of hazardous fluids and/or pressure systems exist within your responsibility. You may have an asset register listing this equipment, with an inventory of hazardous fluids, stating the type and amount of fluid and the nature of the hazard. Procedures and processes should be available to update and maintain these records. An asset register should state the location and function of the equipment and refer to its integrity management records.

See:
- Section 1.1 (How can this report help you)
- Section 1.4 (What equipment the report covers)
- Section 2.4.1 (Asset registers)

1.2 Who is responsible for this equipment?

It is everyone's responsibility to ensure safe working conditions. The division of corporate and individual responsibility should include:

- The owner of the site where the equipment is situated
- The owner of the equipment
- The owner of adjacent equipment
- The user (operator) of the equipment
- The organisation/persons charged with responsibility for its integrity management.
- Inspectors and Competent Person (or User Inspectorate)
- Relevant maintenance and NDT contractors
- Other professional advisers

All these parties have some responsibility for the safety of the equipment and the consequences in the event of failure. Is the chain and division of responsibility well defined, communicated and understood? Are there any gaps in responsibility, particularly at the interfaces, or expectations beyond what could be reasonably assumed? What systems exist for auditing the competency and adequacy of those to whom responsibility is devolved? How does your company keep up-to-date with current industry practises in relation to plant integrity management?

Due note needs to be taken of company culture and governance for effective management of equipment ageing. Good indicators are proactive senior staff benchmark reviews, a positive learning and communication policy, problem tagging, reporting safety–related incidents, empowerment and shared responsibility and decision making. It is insufficient for management to have these as policies; are they really happening on the ground?

See:
- Section 1.2.2 (Who will find the report useful)
- Section 2.1 (Taking responsibility and control)
- Section 2.2 (Company culture)

1.3 What consideration is given to equipment ageing and life extension?

Those responsible for operating and maintaining equipment are expected to be aware of its age, current condition, the mechanisms and rate of ageing and remaining life. The organisational structure, time and resources, and the available information must be sufficient for this awareness to be generated. Evidence of consideration to ageing and life extension may be in the form of:

- Asset management planning
- A periodic report of condition indicators
- Key equipment performance indicators and availability/reliability targets
- Comparative equipment performance reviews
- Reporting and analysis of lost production, incidents, and failures
- Plant integrity review meetings
- Equipment planning and standard setting
- Verification of inspection and maintenance
- Awareness of industry trends through meetings of trade associations, EEMUA, IMechE.etc

See:

- Section 1.1 (How can this report help you)
- Section 1.3 (What's the concern?)
- Section 1.4 (What equipment the report covers)
- Section 2.2 (Company culture)
- Section 3.1 (Managing equipment lifecycle)

2 Management of ageing assets

2.1 What company strategies or policies are in place for managing ageing?

Good companies with significant equipment will have an Asset Management Policy Document. This will identify the risks of failure from the equipment (material and human) together with the general approach to maintaining and assessing the condition of the asset. The Asset Management Policy may refer to a HAZOPS risk study and a Structural Integrity Management Plan for particular classes of equipment setting out the means by which fitness for service is assured and risks controlled.

Most companies will have some form of Maintenance Policy for the routine upkeep of equipment, be it regular, condition or risk based. The same may apply to Inspection and NDT Policy, but it important to understand and differentiate the extent to which this is under the control of the Competent Person (or User Inspectorate). Some companies will have strategies for managing particular threats to their equipment, such as corrosion under insulation or vibration induced fatigue.

See:
- Section 4.5 (Review of schemes of examination and condition monitoring)
- Section 2.1 (Taking responsibility and control)
- Section 2.3 (Setting the strategy)

2.2 What records/documentation about the equipment are maintained?

Good companies are expected to have records and documentation for each item of pressure equipment and permanent containment of hazardous fluids. The data held needs to include the original manufacturer and age, construction and installation drawings and reports, where relevant, a log of operation and any excursions, any leaks and other failures, records of maintenance, replacement parts, repairs and modifications, written schemes of examination and inspection reports. It should be possible to determine easily what maintenance and inspection has been carried out, to get an idea about the current condition and any integrity issues, and to know when the next maintenance and inspection are due, and to identify any backlogs or deferrals.

The integrity and security of these records are very important. Adequate protection against loss is required, particularly when records are computer based. Procedures are needed for the transfer of records when equipment is moved or bought or sold. Equipment records need to be sufficiently accessible by those who may need to use them, yet sufficiently controlled. What records exist? Who has access to them? How are they used? What are they telling you?

See:
- Section 3.3.1 (Indicators and risk factors)
- Tables 2a and 2b (Indicators or symptoms of ageing, and Risk factors for ageing)
- Section 2.4 (Systems for knowledge management and retention)

2.3 Can your company demonstrate it has the competencies required?

You should employ a range of competencies for the management of equipment ageing. Technical knowledge is needed about the design and materials of the equipment, the operating environment and hazards, and fitness for service. There should be the necessary practical skills for safe operation, maintenance, welding, inspection and NDT. And there should be the necessary managerial support with knowledge of the relevant Regulations and Approved Codes of Practice, empowerment to create systems and procedures, communication and teamwork. These competencies can lie outside your company, (e.g. for a Competent Person/Subcontractor), but the necessary connections must exist.

These and other competencies may be defined in job descriptions, management organograms and similar documents. The level of experience, supervision and training and certification needs to be appropriate to the task and the responsibility; there are formal requirements for inspection, NDT and welding personnel. Skills passports are a good way of confirming competency and are useful both inside and outside the company. What certification do you require from your subcontractors and external maintenance technicians?

The supply of engineers qualified for pressure systems and hazardous containers is shrinking. What strategies does your company have to ensuring a continuing level of skill and knowledge in the workforce for managing equipment ageing? These may include specific policies for the retention of key competencies, recruitment and training, the management of older staff and succession planning, and the use of subcontractors and professional advisers.

See:
- Section 2.5.1 (Competencies required)
- Section 2.5.2 (Supply issues)
- Section 2.5.7 (Training, competency and certification of skilled personnel)

2.4 What provisions are in place for the retention and use of corporate knowledge in relation to equipment?

The corporate retention of knowledge in relation to equipment in your company is important to ensure that an adequate history exists whereby current integrity may be assessed. A properly maintained system of record keeping and documentation is a good starting point, but there are instances where knowledge can be lost and particular care is necessary. These include the conversion of paper records to computerised recording systems, the transfer of information during change in ownership or use, or changes in the companies or people responsible for maintaining or inspecting the equipment.

You should be aware of the dangers of obsolescence in both equipment, and the skills necessary to maintain and repair it, and take due precautions. Maintenance manuals and spare parts may become scarce, and it may be unsafe to assume the modern replacements will fit. Some skills, such as the riveting of boilers, are now rare and you should be taking precautions for retaining these if they are important to your business.

See:
- Section 2.4 (Systems for knowledge management and retention).

3 Identification and control of ageing

3.1 Does the plant/equipment have a retirement date?

Some companies plan a life cycle for their plant/equipment, and have a date for retirement/ replacement. If your company is one of these, you should ensure that the retirement date is soundly based and takes the integrity and ageing of the equipment into account. Where decisions are made to continue operation beyond that originally planned, these must have a proper technical justification.

A specified design life for equipment may be a guide to the retirement date, but is not necessarily a good measure on its own. Equipment that has been well managed and is in good condition may continue to be operated well beyond its original design life. Conversely, equipment in an aged condition where design assumptions have proved inaccurate may need to be retired before the design life is reached.

See:

- Section 3.1 (Managing equipment lifecycle)
- Section 3.3 (Indicators of ageing)
- Section 2.3 (Setting the strategy)

3.2 How well is the equipment lifecycle known?

The lifecycle of equipment may be usefully divided into four Stages of Ageing: Post commissioning and Early Life, Risk–based Maturity, Deterministic Ageing, Monitored and Terminal. Companies should know roughly where their equipment is within the lifecycle. How is it performing? What type and frequency of problems are being experienced?

The age of the equipment is one indicator, but not always a good one. Other indicators can be obtained from documentary evidence, leading and lagging indicators from plant performance, and factors that may promote premature or accelerated ageing. Knowledge of the current condition from inspection and maintenance and changes since the last outage, together with general impressions from plant walk-down, are important in order to know the Stage the equipment has reached in its lifecycle. At which Stage is your equipment?

See:

- Section 3.1 (Managing equipment lifecycle)
- Table 1 (Description of the four stages of ageing)
- Section 3.3 (Indicators of ageing)

3.3 How aware is your company of the indicators of ageing?

Reviews of documented information about the equipment, including reassessments of design in relation to operating history, are a useful way to identify the potential for ageing after a period of service. A historical appraisal of operations, maintenance, inspection, test and repair records may show trends. Leading indicators of ageing could include poor welding or poor design features in a corrosive or cyclic environment, reoccurring service problems and unplanned shutdowns, or changes of service and external hazards.

Those responsible for equipment on a day-to-day basis need to be aware of the tell tale signs of ageing from plant performance. These might include leakage, surface damage such as blistering or corrosion, or reductions in plant efficiency or lack of process stability, which might indicate pipe fouling or valve pump/seizure, or excessive vibration and movement. There are many lagging indicators such as these and good companies will be aware of them. How well trained are your staff to recognise the signs and empowered take action?

A good company is also aware of the many factors that can promote premature or accelerated ageing. These can originate at any stage of life, starting at the time of design and construction (e.g. welding defects, inappropriate storage) or during commissioning (e.g. overfilling, harsh start-up procedures etc). In operation, ageing can be accelerated or advanced by factors such as poor water treatment, impurities in the feedstock, the effects of agitation, while incorrect or inappropriate maintenance and repair may do more damage than good. Are your staff trained to recognise the signs and empowered take action?

In all of these, the use of qualified and experienced engineers, combined with good control procedures and sufficient empowerment, is the best way to guard against early wear-out and to ensure that the symptoms of ageing have not been overlooked.

See:
- Section 3.3.1. (Indicators and risk factors)
- Section 3.2 (Damage types and mechanisms)
- Section 3.3.3 (Indicators/risk factors of premature or accelerated ageing)
- Tables 2a and 2b (Indicators or symptoms of ageing, and Risk factors for ageing)
- Tables 3a and 3b (Indicators/Risk factors that can be inferred from Design & Manufacturing data, or from Service data)
- Table 4 (Factors promoting premature or accelerated ageing)

3.4 Does the approach to inspection take account of the stage of equipment life?

The approach to inspection planning and methods should take account of the stage of life the equipment has reached. The normal policy is for a first examination, followed by risk based inspection, deterministic inspection and monitored inspection. Many companies are moving away from fixed inspection intervals and an unchanging inspection regime to one that recognises the different and changing threats to integrity during life and the benefits of avoiding inspection where it is safe to do so.

New equipment, or older equipment entering a new application, would normally have a first inspection within the first two years of service. This is to confirm the design assumptions and manufacturing integrity are realised in service, to detect any early service problems and to set benchmarks of condition against which changes from later inspections may be measured. When operations are stable and favourable experience has been gained, the approach to inspection can become risk based, possibly with longer intervals and reduced scope, to confirm an expectation that the rate of damage from assessed ageing mechanisms is small and that no unexpected mechanisms are occurring. Risk-based inspection needs to be robust?

After indicators of accelerating ageing are detected, a more deterministic approach to inspection, using methods that quantify the extent of damage, is needed. This might include techniques such as such as corrosion mapping, automated ultrasonic testing, using phased arrays and focused probes, and time-of-flight diffraction. Finally, as equipment approaches the end of its useful life, on-line monitoring of rapidly deteriorating or severely damaged areas, such as leak detection, may become necessary to ensure safety in addition to periodic deterministic inspection.

When ageing damage and failures are detected, it is good practice to identify the root causes and the rate at which damage may be occurring. Does it relate back to the original assessment? What are the trends? What is the data telling you? Those responsible for inspection should be aware of the HSE report that exists in regard to risk based inspection planning and for the reliable application of manual ultrasonic and other methods of NDT.

See:
- Section 3.4 (Inspection and non-destructive testing)
- Section 3.4.1 (Approach to inspection strategy over the four stages of ageing)
- Table 6 (Methods of inspection for the detection of various ageing damage mechanisms)

4 <u>Addressing ageing through assessment and remediation</u>

4.1 What options are considered when ageing related damage is detected?

Good companies consider a range of options to adopt when ageing damage is detected. These can range from scrapping the equipment, or removing the damage, with or without a repair, to undertaking a fitness-for-service and remnant assessment, and living safely with the damage, possibly by de-rating or more regular monitoring. The avoidance of intervention and difficult repairs is often beneficial to future integrity. Flaws attributed to original manufacturing need assessment, considering the potential for growth in-service, but repairs are only necessary when margins are low or the data for a FFS assessment is uncertain.

See:

- Section 4.1 (What are the options?)

4.2 How is fitness-for-service and remanent life assessed for aged components?

Fitness-for-service assessment requires the application of recognised up to date procedures by integrity engineers with sufficient training and competence for the level of assessment adopted. The choice of procedures (e.g. BS 7910, API 579) is less critical providing linkages to the original design standard (e.g. BS or ASME) or industry specific applications are recognised. While procedures are designed to be conservative, few contain explicit factors of safety. The appropriate choice (e.g. lower bound) of the input data (e.g. defect size/wall thickness, material properties) within the range of variability is important to ensure safety with a sufficient margin for error. Sensitivity analyses are beneficial where data are uncertain.

Fitness-for-service assessment is important when equipment has been in-service beyond that period for which comparable favourable experience elsewhere can be demonstrated. This applies particularly to defining a fatigue life for equipment where the original construction code is not known or did not contain fatigue rules, or where the operating history is uncertain or has exceeded the design fatigue life or fatigue analysis exemption limits. In these instances, companies are expected to have undertaken an appropriate inspection and assessment to determine a remnant fatigue life based on the condition of the equipment.

Methods exist for the assessment of the effects of corrosion (or corrosion-erosion) which include general wall thinning, local thinned areas and pitting. Companies reporting stress corrosion cracking should be aware that it is very difficult to make predictions about fitness-for-service because the rate of cracking can be highly variable and sensitive to the chemical environment. Creep service damage in high temperature equipment requires management using established replication methods or measurements of creep strain, unless cracks are detected in which case consideration of creep crack growth is necessary.

Leak-before-break is insufficient as a permanent guarantee of safety and integrity. Its main use is within a multi-legged integrity case to cover areas where it is not possible or practicable to inspect. It may also be used as an argument to cover a period of operation after a part through defect has been detected and before a full assessment and repair can be made.

De-rating the design and operating conditions for equipment with ageing damage is an acceptable practice that can allow equipment to continue to operate and increase remanent life. Decisions about de-rating need to be supported by fitness-for-service assessment. Companies need to have considered the effect on the rest of the system when particular equipment is de-rated. Will reduced load on one item increase load on another?

See:

- Section 4.2 (Assessment of fitness-for-service and remanent life)
- Section 3.4.7 (Information for assessment of the damage and fitness-for-service)

4.3 What procedures are used in the event that equipment requires repair?

Both welded and non-welded repairs to equipment are often a source of further problems if not carefully controlled and specified. It is good practice to specify each repair before work begins, and to have considered the impact of the repair within the context of the plant as a whole. Are the practical aspects being considered? For example, is access to the equipment more restricted than when the plant was first constructed?

The removal of surface and near surface flaws by grinding is a skilled operation and appropriate training is needed to ensure the operators can machine a smooth profile and avoid sharp features. A check should be made on whether the remaining wall thickness is adequate. Restoration of wall thickness by welding requires qualification of the welding procedure and the welder, and the use of a welding procedure designed to minimise the risk of high hardness in the heat affected zone (HAZ) of the parent material.

Many companies use proprietary composite plugs, wraps and bands, clips and clamps to seal leaks. Some of these repairs are designed to carry axial load while others are not. Companies are expected to have taken the advice of the suppliers regarding safe installation. All these repairs should be considered as temporary with an agreed period before the repaired area is inspected, and the repair, or the equipment, replaced with something more permanent. Are you aware that an HSE Safety Notice has been issued on repairs to piping?

Welded repairs to existing equipment are difficult to perform successfully and appropriately qualified and experienced welding engineers and welders are essential. Extra procedures (e.g. bake out, pre-heat) to reduce the risk of cracking are necessary in particular circumstances. Post weld heat treatment needs to be carefully considered, since excessive heat can damage surrounding parts and lower material properties, yet insufficient heat may not be effective to stress relieve. Is your company taking the appropriate advice?

See:

- Section 4.3. (Repair and modifications)

4.4 What procedures are in place regarding revalidation of equipment?

When equipment is modified, repaired or when there is a change in the operating conditions, it is necessary to consider the impact of the change on the safety of the equipment and the system. Companies need to revalidate the equipment to the standard of the appropriate design code. You should revalidate generally in accordance with the original code of construction, except where this has been superseded with more onerous requirements.

Proposed changes to operation involving temperature below 0^oC require special attention to ensure that materials have sufficient impact properties. This might be as a result of changing the product to one that requires more refrigeration or having greater flows and pressures in the blow-down system. You should be aware that the HSE has issued detailed report on how to deal with the assessment of pressure vessels operating at low temperatures (HSG 93).

Another situation where equipment needs revalidation is when equipment has been in storage for some time or is purchased second hand. A thorough inspection and dimensional checks are essential to establish the current condition, but these may need to be supported by fitness-for-service assessment. It is risky to buy equipment where the previous operating history is not well known or well documented.

See:

- Section 4.4 (Revalidation of equipment)
- Section 4.4.10 (Revalidation of second hand equipment, reuse, and equipment from storage)

4.5 Do written schemes of examination reflect the equipment's age and condition?

Fitness-for-service assessment, repair and revalidation need to be supported by on-going schemes of examination that address the age and condition of the equipment and the risk of failure. A good test is to see when the schemes of examination were last revised. If the scheme was not changed in line with changes to the equipment, then the extent, nature or frequencies of the inspection probably need to be revised.

Companies should consider the benefits of installing on-line monitoring that could indicate ageing mechanisms in-between outages. A wide range of sensing devices are now available for monitoring parameters such as leaks, vibration, changes in fluid flow or level, product quality and through-put etc. When linked to a responsive operating regime, condition monitoring can play a key part in the management of ageing and when used appropriately can be used to justify extended inspection intervals.

See:

- Section 4.5 (Review of schemes of examination and condition monitoring)

4.6 What policies are in place for determining the end of equipment life?

An economic analysis considering the costs of inspection, maintenance and repair and lost production failure versus the costs of decommissioning and replacement is a good basis for determining end of life. Advanced companies will be undertaking these types of analysis using methods such as net present value to optimise the financial performance from the asset. A proactive replacement strategy is a positive stance to the management of equipment ageing.

See:

- Section 4.6 (Financial criteria for determining the end of equipment life)

APPENDIX 2. CASE STUDIES FROM PLANT AGEING EXPERIENCE

Case Study 1: Not enough attention given to supporting structures

This storage sphere collapsed because one leg became severely corroded and could not carry the weight. A catastrophic failure was narrowly avoided. The lesson here is that supporting structures, although not pressure containing, are part of the system safety and need to be properly protected, managed and inspected (See Section 1.4.1 & 1.4.3).

Case Study 2: Inadequate design and inspection of relief systems

A severe electrical storm resulted in the partial shut-down of the plant. Flammable hydrocarbon liquid was pumped into a process vessel that, due to a valve malfunction, had its outlet closed. Once the vessel was full, the only means of escape for this hydrocarbon was through the pressure relief system and then to the flare line. When a high speed slug of liquid encountered a corroded elbow section the forces were sufficient to detach the section. 20 tonnes of hydrocarbon liquid and vapour was released near ground level, which ignited 110m away and exploded. The result was major fire and destruction of part of the plant with loss of production.

The inquiry found that the designers had not identified the possibility of preferential corrosion at the elbows of the flare lines from the accumulation of stagnant moist sulphur bearing compounds while the line was in the normal unpressurised state. In addition, the flare lines were not inspected, even though they would become pressurised during discharge. This case illustrates the importance of having an awareness of pressure relief systems, and the need to consider the normal operating environment in design and materials selection, and to inspect such systems as part of the normal scheme of examination. (See Section 1.4.3).

Case study 3: Reoccurring bursting disc failure showed lack of shared responsibility and awareness in company culture

At a plant involving pressure equipment, the bursting disc protecting the system from over pressure kept triggering. Company procedures initiated its automatic replacement and reordering. In fact triggering was so frequent that it occurred every two weeks over a period of 18 months and nearly 100 new bursting discs had to be ordered.

No one thought or questioned that there could be a fault due to ageing of the system elsewhere that could be triggering the bursting disc until consultants were brought in for an unrelated problem. The issue here lies with the culture of the company. There was a lack of awareness of the possible reasons and dangers of repeated triggering of the bursting disc, and a failure in communication and sharing responsibility. (See Section 2.2)

Case Study 4: Failure to communicate valve corrosion on an acidic production system led to failure of pipeline

A monel 400 line failed after 5 years of service due to high flow and acidic conditions. During investigation, it was found there had been severe corrosion of control valves on the line. These had simply been replaced, without the information on corrosion and the possible effects on the rest of the system being spread through the operating / mechanical maintenance teams. The fault indicates a lack of shared responsibility, communication and joined up management. (See Section 2.2)

Case study 5: Importance of managing NDT contractors: benefits and costs of changing

In order to monitor defects, an operator employed a NDT contractor to undertake an ultrasonic inspection regime. The contract remained with the contractor for several years, then was changed to another contractor when competitive tendering was introduced. The new contract resulted in a new inspection procedure that gave differing results to the previous reports. The cost of repeat work to establish which results were correct was significantly more than the savings from changing contractor. This case study illustrates the need to manage the work of NDT contractors closely to ensure optimised procedures are used and to ensure consistency in approach when changes are made. (See Sections 2.5.7a & 2.5.9c).

Case study 6: Variable weld quality as an indicator for shortened life of furnace tubes

Furnace tube welds were failing from thermal cracking. The problem was considered to be an age-related failure mechanism, but investigation showed the failures occurred on both old units and newly purchased or repaired items. It was found subsequently that inferior weld quality was a significant contributor to shortening the life of the tubes that failed. (See Sections 2.5.1, 2.5.7b & 3.2).

Case study 7: Indicators of ageing in HDPE storage tanks

High-density polyethylene (HDPE) stock tanks are often used for storage of Hydrofluoric acid, and many other chemicals (e.g. Hydrogen peroxide, Sodium Hypochlorite, Ferrous and Ferric Chloride, Hydrochloric acid, Nitric acid, Sodium chlorate, Aluminium chloride, Sodium hydroxide). Inspection over the years has found that HDPE tanks degrade with time, the nature of degradation depending on the duty. Some duties, such as Nitric acid storage, are much more aggressive than others.

Generally, the sensitivity to individual chemicals is taken account of at the design stage with a specified design life appropriate to the duty. Although a chemical compound may be highly toxic and/or corrosive to the external environment and surrounding population, the affect on the HDPE polymer may be of a very low order. This is the case with Hydrofluoric acid duty, where mechanical tests on the properties of tanks, which have been on duty for up to 23 years, have demonstrated how HDPE performs over progressively longer periods of duty.

The construction material used for the majority of HDPE tanks is a grade of high-density polyethylene, Hoechst Hostalen GM 5010 T2, having high toughness and elongation at break. A recent change in polymer is in the use of a Borealis resin HE 3490 LS, which has similar properties but has an increased resistance to rapid crack propagation and slow crack growth. The tanks are designed to a German standard, DVS2205, (superseded in 2002 by EN 12573), that calculates wall thickness on the basis of estimated creep deformation over the design life.

Application of this standard to the tank dimensions estimates the required thickness of the wall at various heights. A design life of ten years is normally used. It is recognised that there is little deterioration of this polymer over the short term and dependent upon history and fabrication competence, deterioration in tank integrity can be understood and recognised as a lesser factor contributing to the failure process.

Assessment of deterioration has focused on the detection of the following indicators:

(a) Internal visual examination

- Separation of the base circumferential welds from either base or tank wall.
- Cracking in the base or roof circumferential welds either in the hoop direction or traveling at right angles to the weld.
- Separation or peeling of the spiral segments in the base, roof or wall of the tank, particularly at fusion lines.
- Growth of forming defects introduced at the fabrication stage of the shell whilst hot and the growth of cracks from these defects.
- Degrading of the polymer indicated by changes in appearance of the internal surface.
- Determination of weld quality particular to each tank.

(b) External measurement

Inspection to monitor creep during the life of each tank by measurement of the tank circumference requires measurements to be repeated at regular intervals over a long period of time (ideally from new). DVS2205 and EN 12573, specify a maximum allowable strain of 0.75%, which corresponds to an increase in circumference by circa 70 mm for a typical 3m diameter tank. In the evaluation of measured strain, temperature and level of contents are factored into the calculation. In addition to the external circumferential measurement, a full visual assessment of external condition and wall thickness measurement is carried out.

The conclusions from several investigations of this type are that service life can safely be extended up to 25 years. Safe operation for extended periods and the avoidance of additional cost for replacement are key outcomes from these reviews. There is an additional environmental benefit, by avoiding disposal of the severely contaminated tank as waste. This case study illustrates the need for awareness of the damage mechanisms (See Section 3.3).

Case study 8: Factors leading to pre-mature ageing of a heat exchanger

Steam valve leaks resulted in a thermal shock on a tantalum heat exchanger. The unit was isolated and washed with cold water, but the tubes did not cool, as the steam could not be fully isolated. The unit was also hot when cold acid was introduced for start-up. This repeated cycle at maintenance and cleaning shortened the life of the unit. Overly aggressive treatment of equipment, particularly during maintenance, can cause lasting damage and shortened life. (See Section 3.2 & 4.5.4)

Case study 9: Ultrasonic inspection of a storage tank, example of poor NDT practice

The owner of an austenitic stainless steel storage tank had contracted out the inspection of the welds to an NDT contractor. The welds were of various configuration and were about an inch or so thick. The NDT contractor was required to carry out a full volumetric inspection of each of the welds against acceptance criteria provided by the owner.

On scrutiny of the inspection, by a third party, it was discovered that the contractor had been applying a standard inspection procedure, written in accordance with BS 3923 (now replaced by BS EN 1714). The contractor was completely unaware of the problems associated with inspecting stainless steel welds using this type of procedure (see Figure 1 below), and the need to use specialist procedures adapted to deal with the behaviour of the material.

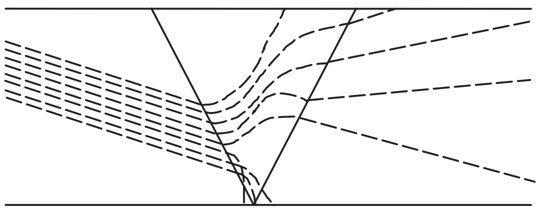

Figure 1

Beam is spread widely due to rapidly changing grain orientation on left-hand side of weld. Example shows 70° scan does not provide coverage on lower right-hand side of weld, leaving any flaws in this region undetected. False indications, at various ranges, are also caused by beam bending down to weld root and upwards to weld cap - inspection requires specialist procedure

When the NDT operators, who were applying the procedure, were questioned by the third party it was discovered, not surprisingly, that they were having difficulties carrying out the inspection, but as instructed were 'struggling-on' to complete the inspection as required by their employer. The completed inspection of each of the welds was almost worthless. Worst-still, the inspection was providing a false assessment of the integrity of the tank itself.

While this might be an extreme example of the technical shortcomings of an NDT contractor, it serves to highlight the problems that can arise when a plant owner/operator discharges all responsibility for NDT to his contractor.

Plant owners/operators are advised to carry a level of NDT expertise 'in-house' commensurate with the type of plant owned/operated and the range of inspections performed. The level of expertise should include a Level 3 certified individual or equivalent who should have an active role not only on the NDT service side but in the procurement of NDT services. (See Sections 2.3.4, 2.5.7a and 2.5.9c).

Case Study 10: Ultrasonic inspection of a storage sphere, example of good NDT practice

An owner of storage spheres, a large UK company, contracted out the inspection of the welds to a NDT service contractor. The butt-welds were about 20mm thick and the material was carbon steel. The NDT contractor was required to carry out an inspection of each of the welds and report all flaws indicative of cracking.

The welds could be inspected by (stand-alone) time-of-flight diffraction in a single D-scan pass. However, it was agreed that due to a combination of wall thickness and the embedded location of the flaws of concern, manual pulse-echo ultrasonic testing would also be used to further investigate and sentence suspect areas. This method of working was proposed by the NDT contractor and accepted by the plant owner even though the inspection would take much longer (than a stand-alone TOFD inspection). It would also be more expensive.

In the event, this method of working proved to be very necessary given the poor condition of the parent material and the quality of welding. This was typical of a fairly old fabrication where correct sentencing based on TOFD data alone would have been very difficult. This way of working is best practice when TOFD is used as a flaw detection tool.

This case study is a good example of an informed purchaser of NDT services (in this case, the owner) recognising the benefits of getting a proper inspection matched to the material condition rather than purchasing an inspection just to meet code/regulatory requirements. (See Section 3.4.1)

Case study 11: Fitness-for-service assessment revalidates subsea pipeline welds

The fitness-for-service (FFS) of girth welds of a subsea 10in diameter, API 5L X60 offshore oil pipeline was called into question after the fracture resistance of the weld metal was found to be variable and sometimes poor at the minimum design temperature of -10°C. The results of the testing after the pipeline had been laid indicated Charpy values as low as 16J and fracture toughness CTOD values measured at the minimum design temperature ranging from 0.03mm to 0.54mm. An integrity case had to be made for the loads under normal and trenching operations.

Fracture mechanics tests were conducted and fitness-for-service assessment procedures were used to assess the significance of potential welding defects. CTOD tests were carried out on specimens notched in the weld centreline. Fracture mechanics analyses were conducted based on the Level 2 FAD flaw assessment procedure from BSI PD6493:1991 (superseded by BS 7910).

In addition to service and trenching stresses, allowance was made for residual stresses remaining after welding. Since the magnitude of the residual stress was uncertain, it was assumed to be tensile and initially equal to the parent pipe yield strength (448N/mm^2), but was allowed to be relaxed by the applied stress, in accordance with the FFS procedure. A maximum misalignment of 2mm was assumed; this gives rise to an additional local bending stress that can affect the risk of fracture or plastic collapse.

The largest possible size of fabrication flaw that could be present was one that might just have escaped detection during fabrication NDT. This was assumed to be surface breaking, not exceeding one weld bead height (3mm maximum) and with the maximum length acceptable to BS 4515, which was 25mm. This was significantly smaller than the minimum flaw size calculated that was expected to cause failure either by fracture or plastic collapse.

Therefore it was shown that despite the poor toughness, the girth welds were tolerant to possible fabrication flaws and fit-for-service. This case study[1] illustrates the importance of obtaining all the relevant properties of materials and welds before fabrication and installation and optimising the manufacture. It also shows the power of fitness-for-service assessment. (See Section 4.2).

[1] (A full report of this case study, written by H G Pisarski and A Muhammed, was presented at the 3rd International Pipeline Conference, Brugge, Belgium, May 2004.)

Case study 12: Need to specify repairs

An example of an unspecified repair was a shaft where corrosion and wear had occurred in two locations. The repair shop was asked to "repair damaged areas". The work carried out was to simply apply a 13%Cr thermally sprayed metal coating to restore the physical dimensions. When completed, this repaired item was returned to store, with little evidence of the repair. When called into service approximately 2 years later, the item failed within a month as the two repaired surfaces were of molybdenum and Nickel alloy "276" and the repairs were clearly unsuitable for the duty. (See Sections 2.4.5(b) and 4.3)

Case study 13: Need for revalidation as a result of a change to plant materials

Corrosion in carbon steel condensers was considered to be excessive, and the units were changed to stainless steel. However, this resulted in local pitting and SCC on the water-side as a result of concentration of solids at the back of the tubesheet. This case study illustrates a lack of awareness of the effects of the water chemistry and the need to revalidate the selection and materials and design when making modifications to plant in-service. (See Section 4.4)

Case study 14: Not maintaining records after modification

As an example of not maintaining records after modification, it was once found that a replacement small condenser would not fit the specified berth. The available exchangers had been shortened by cutting back tubes (to save repair costs, without loss of efficiency), but this had resulted in exchangers of differing sizes for the same location. (See Sections 2.4.5(b) and 4.4)

APPENDIX 3 - INSPECTION PROCESS MAP

Figure A3-1 below shows a map of the processes in inspection that applies at any stage. It equally applies when the approach to inspection is both *confirmatory* and *deterministic*. The accompanying text discusses the key elements of the process in general terms in the context of plant ageing.

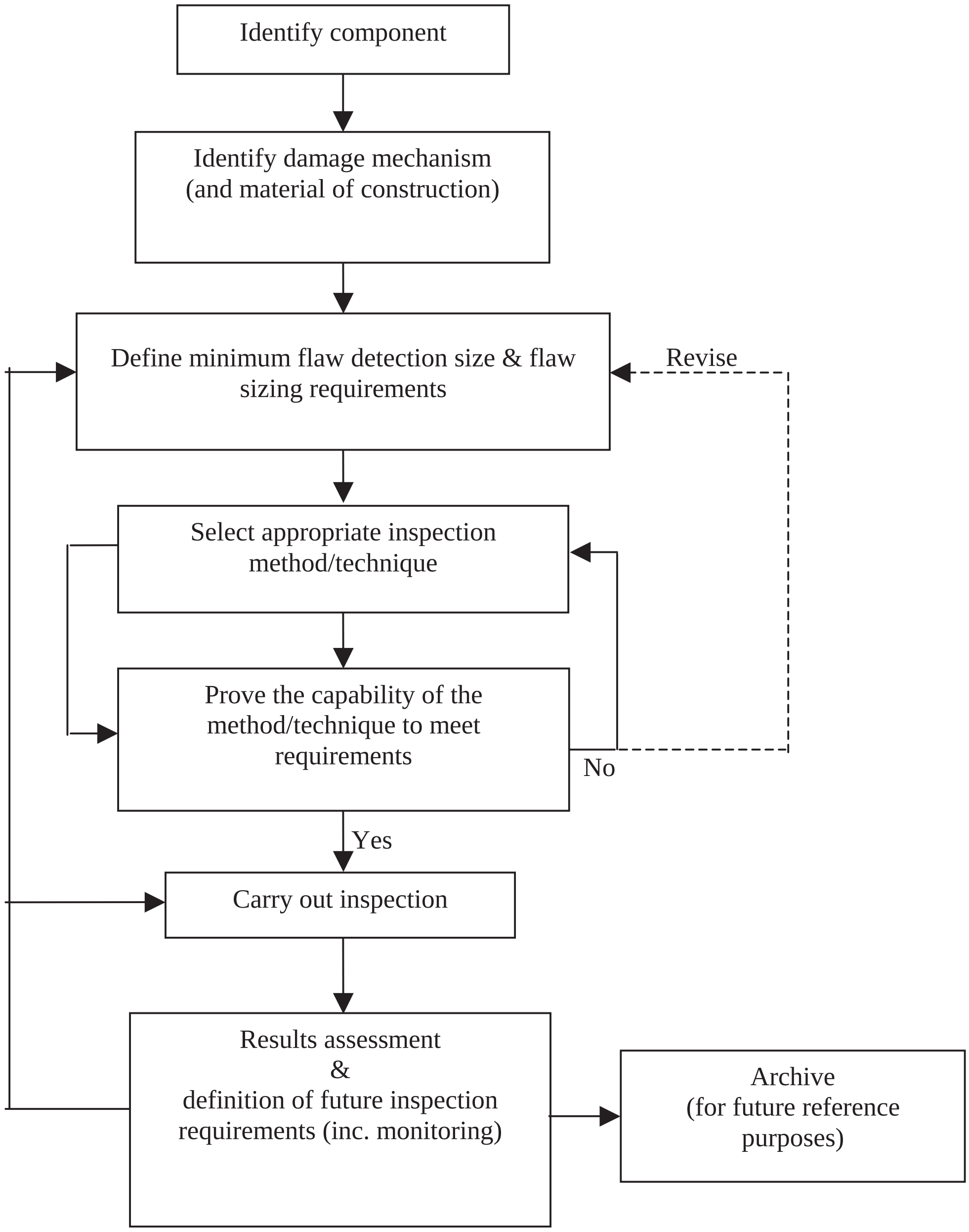

Figure 1: Inspection Methodology

Identify damage mechanism

The identification of the damage mechanism(s) sought is the proper starting point for any planned inspection. An inspection that is targeted at a specific flaw type(s) will always be more effective and be more useful than an inspection of a component that is carried out 'blind' so to speak.

The identification of flaw types will come from a number of sources namely:

- History of component/plant operation
- Data from previous inspections
- Information from previous component failures
- Expected degradation e.g. corrosion of pipework
- Integrity issues from related components/plants
- Component/plant assessments e.g. implementation of risk-based methodologies
- Construction records.

Define minimum flaw detection size & flaw sizing requirements

The next step is to define the minimum size of flaw the inspection must be capable of detecting and the flaw sizing requirements. For plant in its early stages of ageing (Stage 1 or 2) were design margins are still well intact and deterioration mechanisms such as creep or fatigue are not an issue the demands on inspection need not be as great as for the later stages of ageing (Stage 3 or 4). Here the requirements will often be set by a fitness-for-service assessment of the component which can place strong demands on inspection. For example, an inspection to detect stress corrosion cracking in a vessel may have the following requirements specified:

- Minimum flaw detection size: 12mm length x 3mm height;
- Flaw sizing: within ± 3mm length, ± 1mm height.

The above performance requirements are what the selected inspection method/technique will be proved against. With this in mind, requirements should not be specified that cannot be met by the method/technique in practice.

Select appropriate inspection method/technique

The next step is to select the appropriate inspection method/technique, which more often than not will involve NDT. Selection of the appropriate NDT method/technique will come from consideration of the following:

- Damage mechanism identified (inc. its location) and its expected propagation;
- Inspection performance requirements (inc. future monitoring, if applicable);
- Component material;
- Component geometry;
- Inspection access (inc. component surfaces available for carrying out inspection);
- Inspection conditions e.g. high component temperature;
- Contamination implications of applying the method/technique e.g. penetrant testing of stainless steel components.

An example is now given below that features a plant component in the later stages of ageing (Stage 3 or 4).

Example

Stress corrosion cracking has been identified as a potential problem from a leak that has occurred on a similar type vessel. An inspection of the vessel is thus required to determine whether or not stress corrosion cracking is present and, if present, to quantify its extent.

Component	Fermentation vessel supported by a channel welded to the bottom portion of the vessel wall adjacent to the bottom dished end.
Damage mechanism	Stress corrosion cracking (SCC) in the wall of the vessel initiating at the root of the support channel to vessel wall weld and running circumferentially around the vessel.
Inspection performance requirements	Detection requirements for SCC: 10mm length x 2mm height Sizing requirements for SCC: ± 5mm length; ± 1mm height *Note, inspection data to be recorded in a suitable format that will facilitate future monitoring*.
Component material	Stainless steel vessel wall. Carbon steel support channel.
Component geometry	Cylindrical vessel (3m diameter) with hemispherical dished ends. 8mm wall thickness.
Inspection access	Inner surface. No restrictions for NDT.
Inspection conditions	Ambient temperature.

NDT method/technique selected

Because any SCC would be an embedded flaw wrt the inner (inspection) surface of the vessel, a volumetric NDT method is required. Of the two available volumetric methods, radiography and ultrasonics, radiography cannot meet the inspection performance requirements leaving ultrasonics as the only available method. Because the component geometry at the initiation site (root of the support channel to vessel wall weld) is complicated and the inspection performance requirements are challenging, an ultrasonic inspection technique that can record and store inspection data for post processing and evaluation is required.

Of the specialist techniques available, both pulse-echo and twin probe time-of-flight diffraction (TOFD) techniques can meet the inspection performance requirements. Of the two techniques, TOFD just has the edge, in this particular case, given the nature of the inspection (one specific flaw type at one specific location) and the fact that future monitoring is a requirement (an inspection task particularly suited to TOFD). Therefore, for this particular inspection, an ***ultrasonic TOFD technique*** has been selected.

To aid selection of the most appropriate inspection method/technique, the capabilities/limitations of the various NDT methods/techniques used for the detection and assessment of specific degradation mechanisms is contained in Appendix 4.

Prove the capability of the method/technique to meet requirements

The next step is to prove that the selected NDT method/technique is capable of meeting the detection and sizing requirements specified for the inspection. This usually involves some form of qualification of both the inspection procedure and the inspection personnel.

If the technique to be used is routine, as could be the case for plant in the early stages of ageing (Stage 1 or 2), the qualification should be straightforward. It may only require the documentation of the procedure's capability (supported by previous work, if appropriate) and the use of certificated personnel. However, if the requirements are challenging it would be desirable or necessary to carry out practical trials, using a representative test piece, to demonstrate the capability of both the procedure and the personnel.

If the technique to be used is more advanced, as could be the case for plant in the later stages of ageing (Stage 3 or 4), the qualification will almost certainly require the conduct of test piece trials to qualify the procedure and the personnel as the technique will more than likely be specific to the component being inspected. Also, if the requirements are challenging and/or the consequences of component failure are potentially severe then the test piece trials will need to be supported by a document called a technical justification (TJ).

The TJ is a dossier of information that provides evidence that the inspection is capable of meeting the specified requirements. The TJ might include physical reasoning (inc. identification and discussion of the essential parameters of the inspection), mathematical modelling and inspection results. The TJ should also identify 'worst-case' flaws (flaws judged to be the most difficult to detect and size at specific locations) for incorporation into the test piece trials.

The level of inspection qualification performed will be, to a large extent, driven by the safety criticality of the component/business operation considerations.

Carry out inspection

The next step is to carry out the actual inspection using the proven inspection procedure and suitably qualified inspection personnel. For all plant, but in particular old plant which more often than not will be in the later stages of ageing (Stage 3 or 4), the following issues can have a major influence on the quality of inspection that can actually be achieved:

- Access – old plant that has not been designed with in-service inspection in mind can often be configured in such a way that makes access to the inspection site very difficult. This can present particular problems for the application of a more advanced inspection using larger equipment and a manipulator;

- Environment – the quality of inspection that can actually be achieved is greatly affected by the inspection environment and this should be taken account of, where practicable, when proving the capability of the method/technique. Examples of adverse environmental conditions include (i) high noise (ii) high temperature/low temperature where, for example, a manual ultrasonic operator may have to wear protective gloves which will greatly affect his capability to scan properly (iii) the presence of airborne contamination which will require the inspection personnel to wear protective suits and breathing apparatus and (iv) time pressures such as those experienced by personnel working in a radioactive environment;

- Material/weld quality – for old plant that was manufactured to an old design code the material/weld quality may not be too good. For example, plate materials may contain many inclusions and welds a number of manufacturing defects such as slag lines, porosity and lack of fusion. The presence of these types of material/manufacturing flaws can have a significant affect on in-service inspection particularly if using ultrasonic NDT to inspect a weld to determine its condition, as could be the case for plant in the later stages of ageing (Stage 3 or 4). If not accounted for, the existence of plate inclusions will prevent the ultrasonic beam from inspecting the weld properly and if not known the presence of manufacturing flaws, particularly planar flaws such as lack of sidewall fusion, could be mistaken for in-service flaws such as cracks;

- Surface condition – the quality of inspection can be greatly affected by component surface condition. With older plant it is not uncommon to find that the surface condition of the particular component to be inspected needs some preparatory work to arrive at an acceptable roughness and profile. This task should not be underestimated particularly if the inspection surface is clad, lagged or covered with a protective coating e.g. old cast iron pipework covered in a bitumastic coating.

Another issue requiring consideration is on-site safety. This is a particular issue for radiography which requires a lot of health & safety issues to be dealt with prior to its use on-site. Also, entry to certain areas with inspection equipment is only allowed if the equipment is intrinsically safe. With regard to inspection personnel, safety training is a particular issue. As well as the usual site induction training that is required to gain access to a particular site, some inspections will require the personnel to have undergone specific training e.g. for entry to confined spaces, for rope access inspection and for work offshore where training in survival aspects is required.

Ideally, all of the above should have been identified as potential issues prior to carrying out the inspection and their affects assessed in terms of the quality of inspection achievable.

For the more challenging inspections and/or where the consequences of component failure are potentially severe, the inspection should be overseen, ideally by a qualified independent third party, to ensure that the inspection is being carried out in accordance with the requirements of the inspection procedure. In addition, some inspections may warrant that the independent third party carry out some repeat inspection as part of their audit remit.
As with the level of inspection qualification carried out above, the extent of audit activity will be, to a large extent, driven by the safety criticality of the component/business operation considerations.

Results assessment & definition of future inspection requirements

The next step is to assess the results of the inspection in terms of flaw type and acceptable flaw size. With regard to the former, this can often present a problem, particularly for older plant, in distinguishing between inconsequential manufacturing flaws and the in-service flaws of potential concern that the inspection has been designed to detect and size.

When the inspection results have been fully assessed, their significance with regard to component integrity digested and future inspection requirements defined, the results should be stored in an appropriate format and be carefully archived. The format of results including the referencing of inspection data and co-ordinate systems is particularly important for ensuring compatibility with future inspections which could include monitoring.

Future inspection requirements could be defined as follows:

- Carry out a repeat inspection (monitor) in X months or X years;
- Carry out a different inspection in X months or X years (which will involve the definition of new inspection requirements, the selection of an appropriate inspection method/technique etc.).

Note, component monitoring is covered in section 4.5.5.

APPENDIX 4 - CAPABILITIES/LIMITATIONS OF THE VARIOUS NDT METHODS/TECHNIQUES USED FOR DETECTION AND SIZING OF DAMAGE

	NDT Method/Technique	Capabilities/Limitations
Main NDT methods *(Generally applied manually)*	Visual Inspection (1)	Can detect surface breaking flaws. Better capability when special optical aids are used. Capability is heavily dependent on access, component surface condition and the level of lighting. Cannot determine flaw height.
	Penetrant Testing (2)	Can detect surface breaking flaws in non-porous materials (metals/non-metals). The better the component surface condition the better the capability. Cannot detect flaws filled with foreign material and cannot determine flaw height.
	Magnetic Particle Testing (3)	Can detect surface flaws but only in ferromagnetic materials. Always preferred to penetrant testing for components that can be magnetised as the method is less sensitive to surface condition and the flaws do not have to break the surface for detection. Cannot determine flaw height.
	Eddy Current Testing (4)	Can detect surface flaws in electrically conductive materials (metals). Can test through non-metallic coatings and can measure coating thickness. Some capability exists for determining flaw height via comparison with reference flaws such as notches. High level of operator skill is required to interpret genuine flaw signals form spurious signals caused by component surface condition and local variations in material permeability.
	Radiographic Testing (5)	Can detect surface and embedded flaws. Gives a permanent record of the inspection (the exposed film). Good detection capability for volumetric flaws such as slag lines and porosity in welds. Generally poor detection capability for planar flaws such as lack of fusion and cracks in welds. On-site radiography using gamma radiation (from isotopes) is much poorer at detection than X-radiography and requires a lot of H&S issues to be dealt with prior to its use. Cannot determine flaw height.
	Ultrasonic Testing (6)	Can detect, characterise and size (inc. height) surface and embedded flaws. Can test through paint coatings and metallic cladding and can measure component wall thickness very accurately. Materials with large grain structures such as those found in castings, cast iron and stainless steel welds are difficult to inspect. High level of operator skill is required to interpret genuine flaw signals form spurious signals caused by component geometry and, for some materials, grain structure. Its capability to detect small flaws and to accurately determine flaw size, in particular flaw height, means it is used widely as part of fitness-for-service assessments.