HSE

Health and Safety Executive

Plant Ageing Study

Phase 1 Report

Prepared by **ESR Technology Limited**
for the Health and Safety Executive 2010

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Research Report

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HSE

Health and Safety Executive

Plant Ageing Study

Phase 1 Report

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Between 1996 and 2008 it is estimated that there have been 173 loss of containment incidents reported in RIDDOR that can be attributable to ageing plant. This represents 5.5% of all loss of containment events. The limited information provided in RIDDOR about the underlying causes means that it is difficult to identify which events may be age related: the actual number could be much higher than that quoted here.

Across Europe, between 1980 and 2006, it is estimated that there have been 96 incidents reported in the MARS database relating to major accident potential loss of containment which are estimated to be due to ageing plant. This represents 28% of all reported 'major accident' loss of containment events in the MARS database and equates to an overall loss of 11 lives ,183 injuries and over 170Million € of economic loss.

As the MARS data provides the more detailed and comprehensive insight into the incidents and causal factors and is specifically related to potential major accident hazard events, it is considered that this represents a more realistic indication of the extent and severity of ageing plant and its contribution to major accidents. This leads to the conclusion that ageing plant is a significant issue.

Onshore chemical plant in the UK is ageing. Health and Safety Executive (HSE) field inspectors often have to consider the Operators' safety justification for continued use of ageing plant taking account of a variety of issues such as usage, design life, known research, known operational and failure history, maintenance and inspection history, etc. The issues also need to be considered against a background of increasing competition from overseas, and the pressure on resources and investment which this has had over recent years, with reductions in manning levels, early retirement of experienced staff, and pressure on operating budgets.

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HSE Books

Executive Summary

Between 1996 and 2008 it is estimated that there have been 173 loss of containment incidents reported in RIDDOR that can be attributable to ageing plant. This represents 5.5% of all loss of containment events. The limited information provided in RIDDOR about the underlying causes means that it is difficult to identify which events may be age related: the actual number could be much higher than that quoted here.

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The HSE have commissioned this study with the objectives to:

- Identify whether or not ageing is an issue contributing to plant HSE performance.
- Determine which types of assets are affected and in what way.
- Define "ageing" in general terms and, if appropriate, for specific asset types.
- Establish ways in which HSE inspectors can identify ageing issues on sites.
- Identify risks associated with plant ageing.
- Identify best practices in management of ageing issues.
- Understand any differences in plant ageing that may exist in different locations throughout the UK.
- Develop a Delivery Guide on Plant Ageing for use by HSE Inspectors.

The project is envisaged in two phases. This report summarises the findings of Phase 1, which had the objectives of:

- Estimating the extent to which ageing is an issue contributing to plant HSE performance, and whether this is significant in risk terms.
- Evaluating if there are any regional trends or variations within the UK that could be used to prioritise ageing issues

The overall aim of Phase 1 was to establish if ageing was a significant concern, and to identify any particular failure mechanisms or ageing anecdotes by analysing the available incident data to guide Phase 2 with its focus on the technical issues and a delivery guide for inspectors.

It is important to have a clear definition of what is meant by ageing plant. The term "Ageing Plant" is not just associated with its age and design life but importantly involves wider factors that influence its degradation.

Previous work by HSE [1] defined ageing and ageing plant as:

"*Ageing is not about how old your equipment is; it is about its condition, and how that is changing over time. Ageing is 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 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."

Although this definition was largely aimed at process containment, it does capture the essence of ageing and has been adopted for this project.

Overall, ageing plant is plant which is, or may be, no longer considered fully fit for purpose due to age related deterioration in its integrity or functional performance.

It is worth recognising that the original design life for chemical plant, is typically of the order of 25 years. This would place any plant commissioned before 1983 in this category – a substantial proportion of chemical and process plant in the UK probably falls within this definition. However for Electrical, Control and Instrumentation (EC&I) equipment, lifecycles are often significantly shorter than lifetimes of main plant. This is especially so for modern digital plant for which a lifecycle (start of operation to replacement) duration of 10 to 15 years may be more appropriate.

From an HSE perspective, there is a need to be able to identify those sites and installations where ageing may present a significant increase in risk. This will depend on several factors, including:

- The inherent hazards and risks of the installation
- The propensity of the installation to ageing related deterioration or damage
- The likely types of ageing mechanisms and where and how these could present themselves
- The extent to which ageing is being effectively managed

[1] Plant ageing, Management of equipment containing hazardous fluids or pressure, HSE Research Report RR509, HSE Books, 2006

The approach to Phase 1 has been to conduct a detailed review of available incident data to firstly ascertain if ageing is a real issue and secondly to begin to form appropriate questions that will be eventually used within a Delivery Guide focused on plant ageing.

The key databases interrogated were RIDDOR, MARS (EU Seveso II major hazard Incidents) and MHIDAS (Worldwide major hazard accidents).

In terms of major accidental potential events at major hazard installations, the MARS data provides the most appropriate basis to assess the significance of ageing. The study has determined that approximately **60% of incidents are related to technical integrity and, of those, 50% have ageing as a contributory factor**. It is therefore concluded that plant ageing is a significant issue.

These findings support the view that ageing plant is a significant issue, and one that is likely to increase with time as assets age. It is therefore considered timely for the HSE to undertake work into the issue and develop a delivery guide to help inspectors identify, prioritise and address ageing plant issues, as proposed in Phase 2 for this project.

The analysis of the RIDDOR and MHIDAS data is less robust. In both cases the descriptive data provided is very limited. This may partly explain why only a small proportion of the events could be identified as possibly ageing plant related.

The 'ageing' findings derived from the MARS database should be directly applicable to UK COMAH installations or other chemical plant when considering major leaks and incidents. However it should be noted that the proportion of ageing related incidents may fall if all RIDDOR type incidents are included, even though the total number of ageing related incidents may increase. This is because many of the smaller operations and maintenance related accidents and spills, etc due to human and procedural type errors would be reportable under RIDDOR, but would be too small to be reportable under MARS. These could dilute the number of ageing plant related incidents.

A significant observation from the data review was that positive identification of incident causes, especially related to plant ageing, is difficult from the text descriptions provided. There is significant variation in the degree of detail provided in the reports which limits the usefulness of the data in this kind of analysis. Experience from the review suggests that a useful development in reporting of incidents would be to include a simple checklist focused on causation, i.e. recording of contributing factors that emerge from the incident investigation.

The various types of plant asset considered in this study have different types of ageing mechanisms. Consequently the questions that should be asked to discover if ageing is an issue on any given plant are, in their current state of development, asset specific. Further refinement of the questions in detailed consultation with HSE is required. It is also proposed to test the developed questions in a number of scenarios to determine their potential effectiveness in the prevention of future incidents.

Some initial assessment of the geographical spread of plant ageing issues has been completed. Initial results, for COMAH sites only, indicate that no geographical variation in ageing incidents is apparent. This analysis will be developed further in Phase 2.

It is anticipated that Phase 2 of the project will include the following activities:

- Complete a detailed assessment and review of all significant identified plant ageing issues. Detailed descriptions of the ageing phenomena in terms of causes and effects will be developed.

- Identify physical means by which all relevant plant ageing phenomena can be detected. Detailed descriptions of detection techniques will be developed.

- Work closely with HSE Specialists and HSE Inspectors to:

    - Check the basic set of questions presented in this report is complete.

    - Refine the questions and identify specific questions for specific plant types, e.g. chemical plant, refineries, COMAH sites etc.

    - Test the questions by applying a series of scenarios, perhaps based on MARS incidents, to determine whether or not the ageing effects could have been detected and prevented.

- Develop the Plant Ageing Delivery Guide question set.

- Develop the geographic analysis of plant ageing incidents to determine if the distribution of ageing effects is as expected. Any apparent anomalies will be raised for discussion with HSE.

Contents

1.0 INTRODUCTION 8

2.0 PROJECT OBJECTIVES 9

3.0 PROJECT STRUCTURE 10

4.0 REVIEW 14

4.1 Methodology 14

4.2 Asset Category Issues 14

4.2.1 Primary Containment Systems 15

4.2.2 Electrical, Control and Instrumentation (EC&I) Systems 16

4.2.3 Structures 17

4.2.4 Safeguards 17

4.2.5 Management Systems 18

4.3 Data Sources 19

4.4 Preliminary Observations 21

4.4.1 Is Plant Ageing a Problem? 21

4.4.2 Primary Containment Systems 25

4.4.3 EC&I Systems 38

4.4.4 Management Systems 54

4.4.5 Structures 62

4.4.6 Safeguards 64

4.5 Review of HCR Offshore Data 73

4.6 Review of Previous Incident Data Analyses 77

5.0 THE DEFINITION OF "AGEING PLANT" 84

6.0 INSTALLED PLANT LOCATION REVIEW 86

7.0 SUMMARY OF RELEVANT PLANT AGEING QUESTIONS 93

7.1 Primary Containment Systems 93

7.2 EC&I Systems 93

7.3 Management Systems 94

7.4 Structures 94

7.5 Safeguards 95

8.0 CONCLUSIONS 96

8.1 General 96
8.2 Primary Containment Systems 97
8.3 EC&I Systems 97
8.4 Management Systems 98
8.5 Structures 98
8.6 Safeguards 98

9.0 NEXT STEPS – PHASE 2 100

Appendix 1 Possible Ageing Plant Topics

Appendix 2 Non-Metallic Materials Failure Mechanisms

Appendix 3 EC&I Incident Examples

Appendix 4 Project Management Issues for Large EC&I Refurbishment Projects

Appendix 5 Databases and Analysis Methodologies

1.0 Introduction

Onshore chemical plant in the UK is ageing. Health and Safety Executive (HSE) field inspectors often have to consider the Operators' safety justification for continued use of ageing plant taking account of a variety of issues such as usage, design life, known research, known operational and failure history, maintenance and inspection history, etc. The issues also need to be considered against a background of increasing competition from overseas, and the pressure on resources and investment which this has had over recent years, with reductions in manning levels, early retirement of experienced staff, and pressure on operating budgets.

HSE Research Report RR 509 "Plant ageing: Management of equipment containing hazardous fluids or pressure" (2006) comprehensively describes a number of key issues associated with ageing plant but its findings are not targeted with recommendations to inform field inspectors when prioritising intervention and enforcement strategies in the field. HSL Report PS/07/06 "Guidance on fire and explosion hazards associated with ageing offshore installations" (2007) is more targeted at dealing with the problems but only looks at offshore oil and gas installations. A HID Intelligent Delivery Guide has been produced recently on the topic of ageing plant (Workstream 2K Inspection – Plant Life Cycle Stage – Ageing Plant, Issued 18.09.08), but this recognises the need for further research to improve the guidance to inspectors and to raise awareness across sectors.

The term "Ageing Plant" is not just associated with its age and design life but importantly involves wider factors that influence its degradation. As a simplistic basis, ageing plant could be considered as plant that is now operating beyond its original design life, typically 25 years. This would place any plant commissioned before 1983 in this category – a substantial proportion of chemical and process plant in the UK probably falls within this definition. However for Electrical, Control and Instrumentation (EC&I) equipment, lifecycles are often significantly shorter than lifetimes of main plant. This is especially so for modern digital plant for which a lifecycle (start of operation to replacement) duration of 10 to 15 years may be more appropriate. There is also evidence of plant suffering ageing effects well within its design life. Therefore, what constitutes ageing plant in different contexts is something which needs to be defined.

The first part of this project is to examine the basic questions concerning ageing plant at a high level. The first of these questions is simply “Is there a problem?”. Following from that are questions concerning the nature of the problem and whether there is any evidence to show that certain areas of the UK industry are more susceptible than others. To answer these questions ESR have examined a number of data sources with a view to identifying those incidents which can be attributed to plant ageing issues. This document sets out ESR’s preliminary findings from the review together with initial views on the types of questions HSE Inspectors could focus on when planning, prioritising and conducting site visits or when investigating plant failures that may have ageing as a contributing factor.

2.0 Project Objectives

The objectives of the project are illustrated on Figure 1 below.

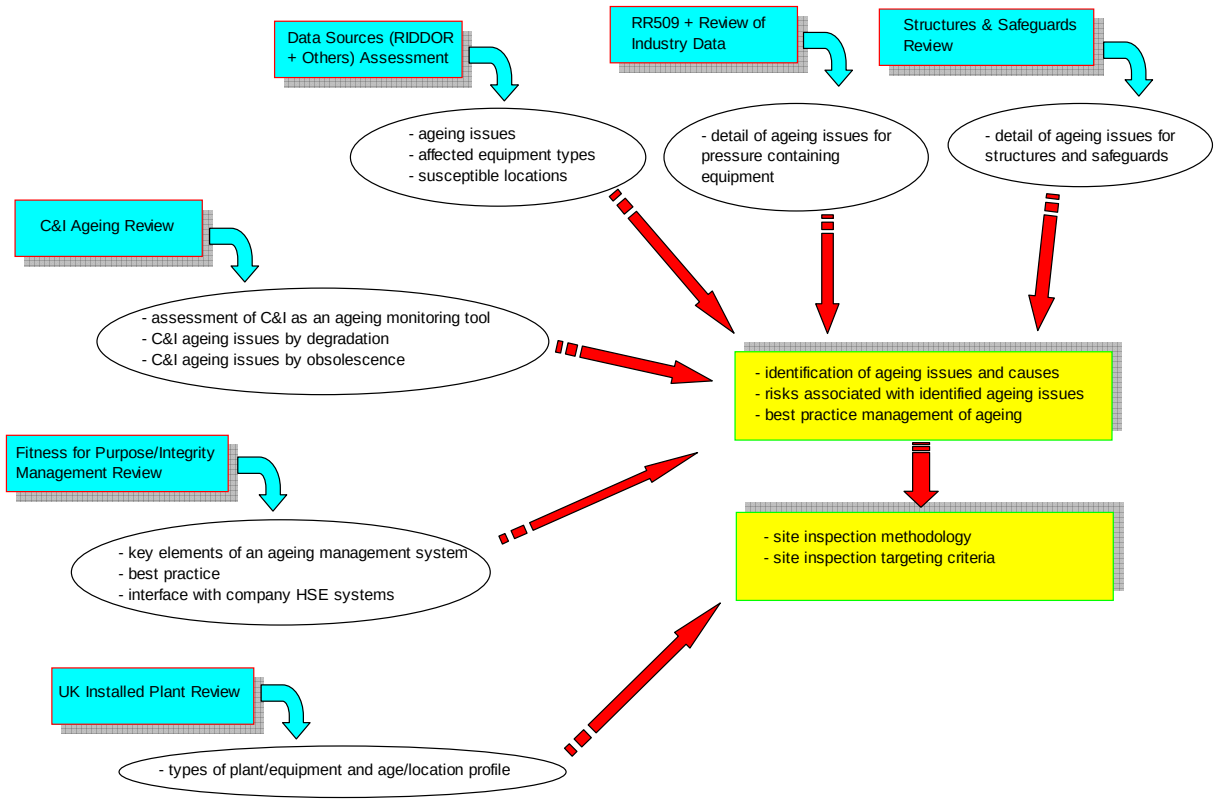


Figure 1: Project Objectives.

In essence the project is intended to:

- Identify whether or not ageing is an issue contributing to plant HSE performance.
- Determine which types of assets are affected and in what way.
- Define “ageing” in general terms and, if appropriate, for specific asset types.
- Establish ways in which HSE inspectors can identify ageing issues on sites.
- Identify risks associated with plant ageing.
- Identify best practices in management of ageing issues.
- Understand any differences in plant ageing that may exist in different locations throughout the UK.
- Develop a Delivery Guide on Plant Ageing for use by HSE Inspectors.

3.0 Project Structure

After discussion with HSE and consideration of the potential issues involved, ESR elected to focus on five asset categories:

- Primary containment systems
- EC&I systems[2]
- Structures (those supporting primary containment systems, atmospheric tanks and human activity on plant)
- Safeguards (secondary containment and handling of hazardous releases, e.g. bunds, drains etc)
- Management systems

Specifically, Table 1 sets out the types of physical asset considered in this study.

Table 1: Physical Assets Considered in this Study.

Category	System
Process Primary Containment	Process primary containment - pipework / static elements, whether at significant pressure or not, e.g. pressure vessels, columns, heat exchangers, storage tanks, open top tanks, pipework, and pipework fittings such as valves, strainers, flanges, ejectors, etc
	Process primary containment - rotating / motive elements e.g. pumps, compressors, turbines, agitators, fans, solids handling equipment, etc
Structures	Supporting structures, civils features and foundations for primary containment
	Supporting structures, civils features and foundations for secondary and tertiary containment, including effluent and storm/ fire-water lagoons and basins
	Structures, civils features and foundations providing impact protection (eg protection from vehicle collision, blast, lifting operations, gas cylinders, etc)
	Structures, civils features and foundations for safe places of work eg controls rooms, offices, workshops, emergency shelters
	Structures, civils features and foundations forming access and escape routes eg roadways, ladders, stairs, gantries, walkways, etc
	Structures, civils features and foundations for safety critical services and utilities eg power distribution, equipment and battery rooms, etc
	Structures, civils features and foundations for safety critical EC&I equipment, weatherproofing, ingress protection, etc
	Structures and civils features that could impact major hazard plant, pipelines or equipment (including EC&I and safeguarding

[2] EC&I systems are considered as a separate asset type in this study as well as being represented as Safeguards. Safeguards as an asset type is insufficient to encompass all EC&I equipment and, given the relative importance of the functions performed by this type of equipment it was considered desirable to analyse it separately.

Category	System
	equipment, cabling, etc) were they to collapse / fail, or which could disperse spilt material if they were to leak/ fail. (eg flood defences, chimneys, communication towers, canal or reservoir embankment, sea defences, buildings, walls, flares/ stacks, tall lighting towers, earth embankments, retaining walls, culverts, bridges, tunnels, underground caverns, etc)
Process Safeguarding Systems	Primary containment of key safety critical utilities and services - pipework / static elements (e.g. instrument air, nitrogen, hydraulics, cooling water, steam, heat transfer oil, etc)
	Primary containment of key safety critical utilities and services - rotating / motive elements
	Integrity and availability of key services such as power supply, UPS, emergency back up generators, battery units, etc
	Mechanical pressure protective systems - pressure/ vacuum relief valves, bursting discs, vents and flares
	Mechanical overfilling protective systems - overflows, emergency dump systems
	EC&I - safety critical process safeguarding systems (trips, alarms, process ESD, etc)
	EC&I - safety critical leak detection and response systems (fire and gas leak / area detection, emergency shutdown systems)
	Ignition source control equipment, eg earthing, equipment enclosures, etc
	Inerting systems (eg nitrogen blanketing and purging)
	CCTV Monitoring of plant areas and escape routes, etc
	Trace heating, cooling or other thermal insulation systems for process insulation or operator protection
Secondary and Tertiary Containment Systems/ Safeguards	Double skin vessels and pipes
	Bunds
	Paved areas, kerbing, gulleys, sumps, etc
	Under soil/ underground non-permeable membranes and land drains
	Drainage systems
	Effluent treatment systems, interceptors, penstock valves for outfall isolation, etc
	Emergency holding tanks and lagoons, etc
Mitigation Systems / Safeguards	Action fire protection and firewater systems, including fusible loops or plugs, fire pumps, fire water lagoons or storage tanks, ring mains, hydrants, monitors, spray and deluge systems, etc
	Passive fire protection systems
	Blast protection and suppression systems
	Inert gas fire suppression systems (eg CO2)
	Impact protection systems e.g. crash barriers, dropped object protection, shielding
	Gas knockdown or inerting systems
	HVAC systems to prevent smoke or gas ingress or protect people or key safety critical equipment
	Communication systems - telephones, radios, PA systems
	Emergency lighting
	Spill kits, and environmental spill / release clean up or control

Category	System
	equipment and systems
	Portable flammable gas and toxic gas monitors etc
	PPE for use in an emergency - BA sets, gloves, chemical suits, face masks, etc
	Rescue equipment
	Emergency showers and eye wash stations
	Portable fire extinguishers and manual fire fighting equipment
External Hazard Safeguards	Flood protection arrangements
	Lightning protection
	Trees or other natural features/ ecosystems that could impact plant/pipelines if they collapsed or caused root damage or burrowing
	Areas prone to subsidence, rock fall or land slip, etc

In addition to the assets described in Table 1 this study also considers the possibility of ageing directly affecting Management Systems in an adverse way. For instance, management systems for inspection may not have kept pace with current best practice, or those for competency may have failed to recognise a skills gap created over time due to falling popularity of a subject area[3].

Ageing issues in each of the identified areas can lead to incidents with significant health and safety implications both for the workforce involved and the general public. As such, the general project flow as illustrated on Figure 2 was developed.

[3] An example might be the current decline in the availability of corrosion engineers and chemical engineers. UK universities have seen a steady reduction in the numbers of students of these subjects that are of primary importance to management of plant ageing issues. A company management system should be able to recognise a skills gap that develops over time and prompt action to mitigate any likely (assessed) effects.

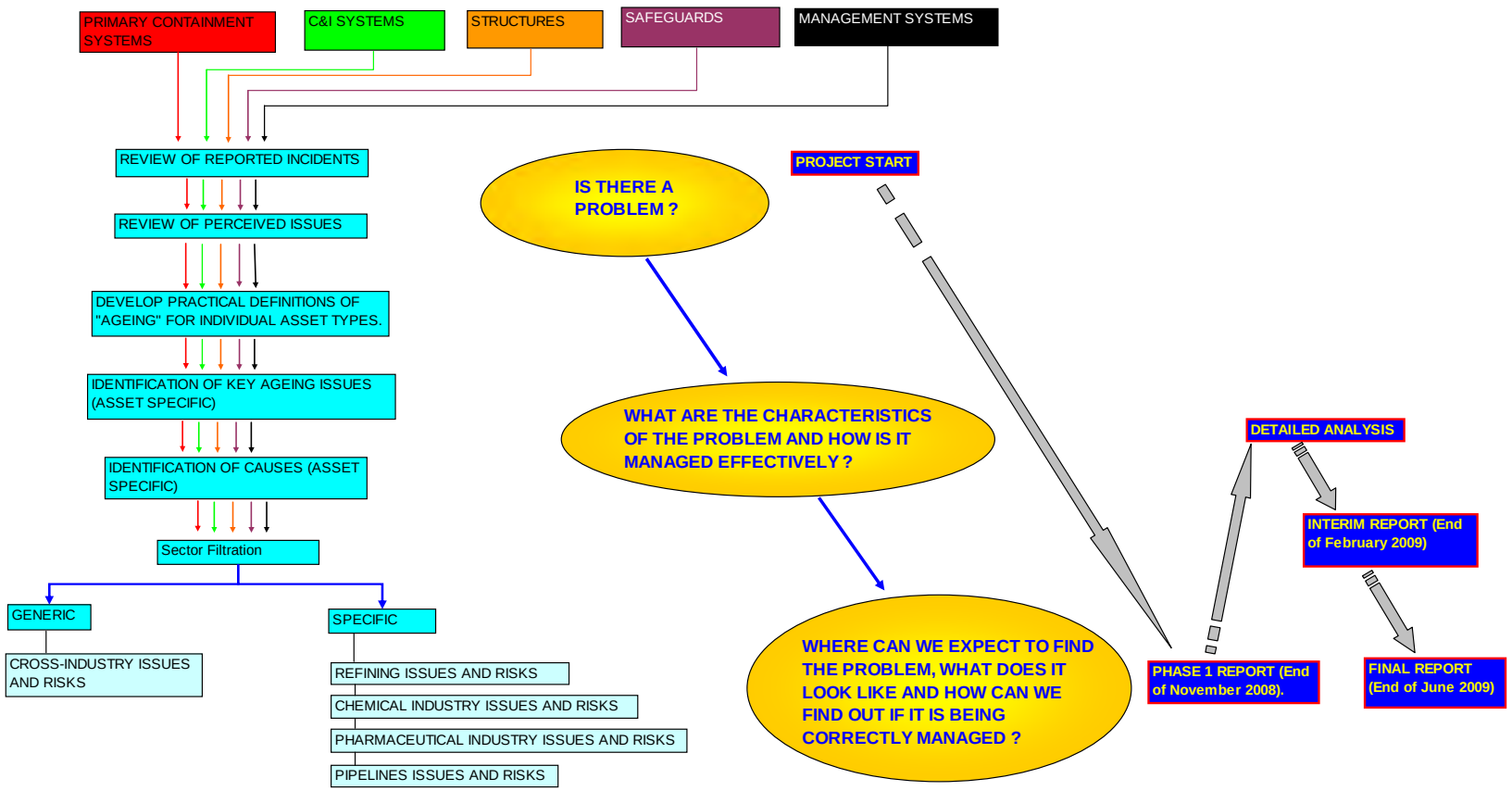


Figure 2: General Project Flow Scheme

4.0 Review

4.1 Methodology

The methodology adopted was to develop a series of “Main Issues” and “Specific Issues” for each asset category that can be affected by ageing and could potentially give rise to significant incidents. These specific issues were derived from the direct experience of a range of HSE Specialist Inspectors and ESR consultants. A number of the issues put forward by HSE that contributed to the development of the lists of identified issues, particularly in the areas of primary containment integrity and EC&I integrity are listed in Appendix 1.

Issues are associated with “Topics” that are intended to lead to the development of specific questions that can eventually be incorporated into the Delivery Guide for use by HSE Inspectors.

The issues were examined against three principal databases of incident reports:

- RIDDOR
- MARS
- MHIDAS

The databases of incident reports were reviewed thoroughly and incidents with ageing aspects, in each of the asset categories, identified using keywords contained within the incident text descriptions. It should be noted that the text information contained in the databases exhibited a very large variation in the level of detail provided within the reports. The degree of variation essentially rendered keyword searching of little use and the only practical way to proceed with the analysis was to consider each report in detail and make a judgement on whether or not ageing was a contributing factor in the incident.

The objectives of the database review were to:

- Provide an indication of the size of the ageing problem, if indeed it exists.
- Identify issues that are of importance in plant ageing in the various asset categories used in the study.
- Identify issues that had not been recognised.
- Provide information on how the identified issues might be suitably prioritised during HSE inspections.

4.2 Asset Category Issues

The following tables present the issues identified in each of the asset categories considered.

4.2.1 Primary Containment Systems

Main Issues
Understanding the plant - what is out there ? Understanding the process - what does the equipment do ? Understanding fault conditions - how can it go wrong ? What are the ageing issues relevant to the plant ? What is best practice for managing the issues ?

Specifics

Topic	Issue	Description
Do they know what they have got and what it does?	1	Incomplete, fragmented or out of date asset register
	2	Knowledge of installation date, procedures and commissioning testing
	3	Knowledge/records of materials and fabrication standards
Do they know what has happened to it since it was installed ?	4	Inspection and maintenance records
	5	Feedback loop, i.e. ability to learn from past experiences
	6	Incident records
	7	Modification records and risk assessments
	8	Inspection and maintenance planning, what are the degradation issues, are they effectively predicted and managed ? Are RBI and RCM effective and applied properly ?
Are they thinking ahead ?	9	What are the ageing issues around corrosion prevention, i.e. when do linings/coatings need replacement or refurbishment ? Is CP maintained ?
	10	Is there an awareness of where ageing uncertainties might lie and is there a plan to reduce the uncertainty ? e.g. CUI
	11	Asset replacement - planning, risk assessment and control of
	12	New materials - what are the issues and are they as known and controllable as those for the materials already in use ?
Process	13	What effect does the process have on the equipment ? Is there an understanding of the rate of any effects that might happen ?
	14	How can the process go wrong and what incremental effects might that have on ageing of the equipment ?
	15	What happens to the plant ageing rate if the plant is worked harder ?
Specific Ageing	16	Is plant corrosion monitored ? What happens to the data gathered ?
	17	Are service hours logged so degradation can be measured as a function of service exposure ?
	18	How is corrosion risk assessed - access to a corrosion engineer ?
	19	Is the potential for rapid degradation understood, e.g. CUI, corrosion at pipe supports, cracking (fatigue, hydrogen, brittle fracture), vibration damage ?
Current Status	20	Is the fitness for purpose of all the equipment known ? How is it assessed ? What are the limits and is it known how fast they are being approached ?
	21	Design Standards Ageing - how does the design of the equipment on site compare with current design standards. If there are differences, then is it undertstood why ?

4.2.2 Electrical, Control and Instrumentation (EC&I) Systems

Main Issues

• EC&I obsolescence is usually ultimately driven by spares availability.
• Most older EC&I equipment will be analogue. Almost all new equipment is digital.
• Demonstrating the safety of new digital equipment requires significant effort.
• The capability to assure the safety of new digital equipment is therefore a key factor in managing the obsolescence of older EC&I equipment. This will require effort, engagement, skills and resources from the operators.

Specifics

Topic	Issue	Description
Do they know what they have got and what it does?	1	Has the operator a full understanding of the significance of the EC&I systems in: (a) immediate process safety such as shutdown systems, (b) process control, (c) mitigation of accidents, (d) monitoring plant for potential safety-related deterioration (process condition monitoring)?
	2	Have all existing EC&I systems been assessed for their required SIL level? Are the operators aware whether the existing (ageing) EC&I systems meet these required SIL levels?
	3	Are the operators aware of potential safety- and business-critical failure modes?
	4	EC&I Common-Mode Failure concerns – separation of control and protection, etc
Are they thinking ahead?	5	Operator's planned EC&I refurbishment strategy (do they have one?)
	6	Ageing processes and lifecycle issues for various types of EC&I equipment
	7	Potential approaches to mitigation of ageing, e.g. environmental control
	8	The business impact of major refurbishment projects
Are they aware of digital safety issues?	9	Digital equipment specific issues: • Smart devices and other COTS components • Safety-related programmable control or protection systems • Operating system software issues • Wireless sensors
Maintenance and procurement	10	EC&I Maintenance, Inspection and Testing (MIT) - planning, risk-based
	11	KPIs for MIT (leading and lagging)
	12	Procurement – spares availability of critical components
	13	Procurement – OEM engagement
	14	Procurement – spares QA and configuration management
	15	Plant history – failure rates of critical components
MoC	16	Management of Change to modern digital equipment – IEC 61508/61511 · Robust MoC processes · functional safety management · SIL qualification software V&V · software QA planning (IEEE 730)
	17	Software configuration management (e.g. for DCS software upgrades)
	18	Project management for large refurbishment projects (e.g. DCS replacement)
Case Studies	19	Accidents and incidents due to EC&I failures – brief case studies

4.2.3 Structures

Structures support primary containment systems, atmospheric tanks and human activity on plant, e.g. gantries, fixed ladders etc.

Main Issues

Understanding structures - what is out there ?
What do the structures do and what must they be able to withstand ?
Maintenance or lack of it !
What are the ageing issues relevant to structures ?
What is best practice for managing the issues ?

Specifics

Topic	Issue	Description
Do they know what they have got and what it does?	1	Are structures uniquely identified in a register How are they assigned maintenance and inspection tasks ?
	2	What design standards have been used for structures and are they still valid ?
Monitoring	3	What loads are the structures rated for and how are these monitored ?
	4	How are the structures inspected and maintained ?
	5	Is there a corrosion monitoring programme for structures ?
	6	Are potential fast failure modes considered in inspection and maintenance, e.g. fatigue ?
Failure Prevention	7	Are any degradation prevention measures in place, and if so, how are they monitored and maintained, e.g. cathodic protection, coatings, engineered mitigations (e.g. vibration dampening, tank wind girders etc) ?
Management	8	Are structures a feature of the integrity management scheme ? How ?

4.2.4 Safeguards

In this context Safeguards consist of equipment and control within secondary containment systems and handling of hazardous releases, e.g. bunds, drains etc

Main Issues

Understanding what safeguards are present.
How is the ability of the safeguarding function assured when it is needed ?
Are safeguards treated as an asset to the company ?

Specifics

Topic	Issue	Description
Do they know what they have got and what it does?	1	What are the safeguards on the plant, where are they and what do they do?
Fitness for purpose	2	Are the safeguards adequate ? What are the relevant design standards and are they themselves adequate for the specific service ?
Recording	3	Are safeguards recorded as "assets" ? If not, how are they assigned maintenance tasks within the company financial system ?
	4	Are records kept concerning safeguard design, installation date, manufacturing standards, testing, maintenance, incidents etc

4.2.5 Management Systems

Main Issues

- Maintenance Management/Operation Procedures In place
- Asset Integrity Management, asset register and asset specific Performance Standards.
- Maintenance/Operational interface good communications
- Risk Assessment, hazard identification, identification of Safety Critical Elements.
- Management of change
- Plant inspections/audit plans
- Incident/Anomaly investigation and tracking
- Corrective action tracking
- Staff Competence, knowledge transfer responsibilities
- Maintenance of standards.
- Review

Specifics

Topic	Issue	Description
Do they know what they have got and what it does?	1	HSE-MS incorporating Maintenance Management
	2	Documented up to date Asset Register
	3	Well maintained standards and procedures
Policy & Strategic Objectives	4	Asset Integrity Management Policy included and understood at all levels.
	5	Performance of assets monitored and discussed at senior level (improvements, failures, anomalies etc.)
Organisation/ Responsibilities	6	Clear lines of responsibility relating to Maintenance Management and the interface with operations.
	7	Good communications between Operations & Engineering e.g. Management Meetings, Reviews,
	8	Job descriptions up to date and understood.
	9	Clear authorisation lines to ensure improvements are made/signed off.
	10	Setting of KPI-KPTs for maintenance and operational systems
Resources	11	Stability in the resource pool to reduce the effect of change.
	12	Job continuity, knowledge transfer, competency development.
Standards	13	Design standards/codes of practice monitored, updated and understood
	14	Competent workforce with an ongoing development programme to cover understanding, working knowledge, can do, skills, mastery levels.
	15	Contractor and third party standards clearly defined and tested
Documentation (hard copy/electronic)	16	Well maintained Asset Register and other identified Maintenance Management procedures.
	17	Clearly identified and easily accessible
	18	Reviewed at clearly defined intervals
Hazard & Effect Management	19	Risk Assessment programme relating to the impact of failure and the effect of process change
	20	Hazard identification, fitness for service
	21	Incident investigation, Near Miss reporting with clear action tracking and close out procedures.
Planning	22	Asset Integrity Management plan incorporating Management of Change procedure in place.
Procedures	23	Clearly defined Maintenance Management procedures
	24	Risk based inspection programme
	25	Management of Change requirements

Main Issues
• Maintenance Management/Operation Procedures In place • Asset Integrity Management, asset register and asset specific Performance Standards. • Maintenance/Operational interface good communications • Risk Assessment, hazard identification, identification of Safety Critical Elements. • Management of change • Plant inspections/audit plans • Incident/Anomaly investigation and tracking • Corrective action tracking • Staff Competence, knowledge transfer responsibilities • Maintenance of standards. • Review

Specifics

Topic	Issue	Description
	26	Technical Safety reviews
	27	Incident reporting, investigation and action tracking systems covering Operations and Engineering/Maintenance activities.
	28	Operational procedures that interface with repair/downtime.
Implementation	29	Clear time based schedules for inspections/audits and close out of actions.
	30	Good communications to ensure responsibilities for implementation of standards and procedures are known and understood
	31	Ensure interface between operations and Engineering
Audit/Inspection	32	Audit plans by both external and internal resource covering Maintenance/Operational activities.
	33	Inspection schedules to identify signs of deterioration
	34	Staff competence to ensure consistency of approach, understanding and level of authority.
Corrective Actions	35	Clearly developed corrective action plans with close out tracking system
	36	Clearly identified responsibilities with KPI/KPT set.

4.3 Data Sources

Accident and incident data from three databases were examined.

1. RIDDOR (UK only): (Reporting of Injuries, Diseases and Dangerous Occurrences Regulations): Under RIDDOR there is a legal duty to report work-related deaths, major injuries or over-three-day injuries, work related diseases, and dangerous occurrences (near miss accidents). These reports are held on a HSE database and enables the Health and Safety Executive and local authorities to identify where and how risks arise, and to investigate serious accidents. A sub-set of the RIDDOR database has been provided containing a total of 3142 major, loss of containment accidents in the UK process industry. The period covered by this data is from 1996 to 2008. The initial filtering and formatting of the RIDDOR data to extract the loss of containment events was undertaken by HSE data specialists familiar with the RIDDOR and supporting databases.

2. MARS (Europe): The Major Accident Reporting System (MARS) was established to handle the information on 'major accidents' submitted by Member States of the European Union to the European Commission in accordance with the provisions of the 'Seveso Directive'. Currently, MARS holds data on more than 450 major accident

events covering the period 1980 through to 2006. Information submitted to MARS may, where national provisions so require, be kept confidential if it calls into question, for example, the confidentiality of the deliberations of the Competent Authorities and the Commission, public security, personal data and/or files, commercial and industrial secrets, etc. However, without violating these aspects, access to the register and information system is open to government departments of the Member States, industry or trade associations, trade unions, non-governmental organisations in the field of the protection of the environment and other international or research organisations working in this field. The MARS data extract provided by the HSE for this project includes accident descriptions for 348 major accidents across Europe. It has a large number of data fields and sometimes written in poor English. Plant function is sometimes not clear.

3. MHIDAS (Worldwide) : The Major Hazard Incidents Data Service (MHIDAS) database holds details of over seven thousand incidents which have occurred worldwide during the transport, processing or storage of hazardous materials which resulted in or it is considered had the potential to cause off-site impact. This definition includes incidents which incurred casualties, required evacuation of either on-site or off-site personnel or caused damage to property or the natural environment, together with incidents which could, but for mitigating circumstances, have led to the above occurring. Some particular types of incidents, such as those involving radioactive materials for example, are specifically excluded from the database. Incidents are not generally entered onto the database until a year after they have occurred so that as much information as possible can be collected for each incident from a number of different types of journals. The database was formed circa 1985 from several other databases available at that time. The current version of the MHIDAS database contains over 16,000 records corresponding to over 14,000 incidents, and has been used to search for data to support the HSE Ageing Plant project. MHIDAS is an AEA Technology-hosted database. Details of plant and its function can be limited since much of the information is drawn from press reports and insurance databases. An extract of the current database containing 2951 process industry accidents was reviewed.

These databases were searched using an initial set of keywords intended to highlight incident reports where one of the contributing factors could potentially be ageing. Due to limitations of the keyword search approach, these were supplemented by manual reviews of the data to extract any relevant events.

A range of other previous HSE reports were also reviewed as part of the study:

- Loss of containment incident analysis (SPC/Enforcement/90)
- Loss of Containment Incident Analysis (HSL/2003/07)
- Findings from Voluntary Reporting of Loss of Containment Incidents 2005/06
- Findings from Voluntary Reporting of Loss of Containment Incidents 2004/05
- Investigation of loss of containment dangerous occurrences (SPC/Enforcement/132)

These previous HSE reports are discussed in Section 4.6 of this report.

Further details of the database searches conducted and the keywords applied can be found in Appendix 5.

4.4 Preliminary Observations

4.4.1 Is Plant Ageing a Problem?

Examination of the incident reports in the three primary data sources indicated that in two of them, i.e. RIDDOR and MHIDAS, it was difficult to positively assign the issues identified in Section 4.2 to large numbers of reports. This is because reports are either very brief or do not reveal the root causes of the incidents. For example:

"Explosion of valve in oxygen line - This was second explosion of valve in exactly same position in 12 months. Back pressure valve between oxygen vaporiser and filling line, holds 100 bar upstream to reduce velocity through vaporiser. Located where no normal access, so low risk. Previous incident last year - no obvious cause as most of valve consumed in ensuing fire. Investigation continuing."

The explosion in this example may or may not have been caused by an ageing issue. Unfortunately, in attempting to answer the question of whether or not ageing is a problem, such incidents have the effect of diluting the statistics. They therefore have the potential to skew the statistics in either direction depending upon whether they are included or excluded from the assessment. Experience from the review suggests that a useful development in the reporting of incidents would be to include a simple checklist focused on causation, i.e. recording of contributing factors that emerge from the incident investigation. Such a data field could significantly enhance the usefulness of the RIDDOR and COIN databases to the HSE, for example in helping set its priorities and identify trends in key areas of interest.

The data received from the MARS system contains substantially more detail than that routinely kept in the other two principal sources. As such it is possible to have significantly more confidence in the assignment of issues to individual reports, and hence have more confidence in the resulting statistics. It should be noted however, that while the RIDDOR and MHIDAS data are of less use in identifying the *size* of the potential ageing issue they do contain substantial numbers of reports that can be associated with the identified issues and therefore provide extremely valuable information concerning the *nature* of the ageing processes.

In terms of uncertainty in the data analysis, it is concluded that the limited descriptive data provided in the RIDDOR and MHIDAS databases means that a considerable degree of judgement had to be used to assess if a given event was in any way ageing related. The data analysis should therefore be treated with some caution. It is likely that if more detailed data were available, this would show that more incidents were in some part ageing related, so the extent of ageing failures may be higher than estimated in this analysis.

The MARS database provides significantly better information, though by no means fully comprehensive. This has allowed specific causes such as corrosion, fatigue, vibration and erosion to be identified. These mechanisms for containment or structural failure can be classified as ageing related with a high degree of confidence. However, it has been more difficult to determine which EC&I, non metallic structural, safeguards or HSE management system failures related to ageing. The findings for these latter categories should be treated more cautiously as a degree of judgement was required to assess if ageing was an issue, since in many cases the data did not provide any key text that would confirm ageing as a definite causation factor.

Analysis of the MARS data shows 348 reports. 54 of the reports have uncertain or missing causative factors leaving a total of 294 incidents that could be fully analysed.

Figure 3 indicates the proportion of these incidents that could be broadly categorised as due to Technical Integrity issues, EC&I issues or Human Factors / Procedural type issues. This indicates that approximately 60% of the MARS incidents are technical integrity or EC&I related.

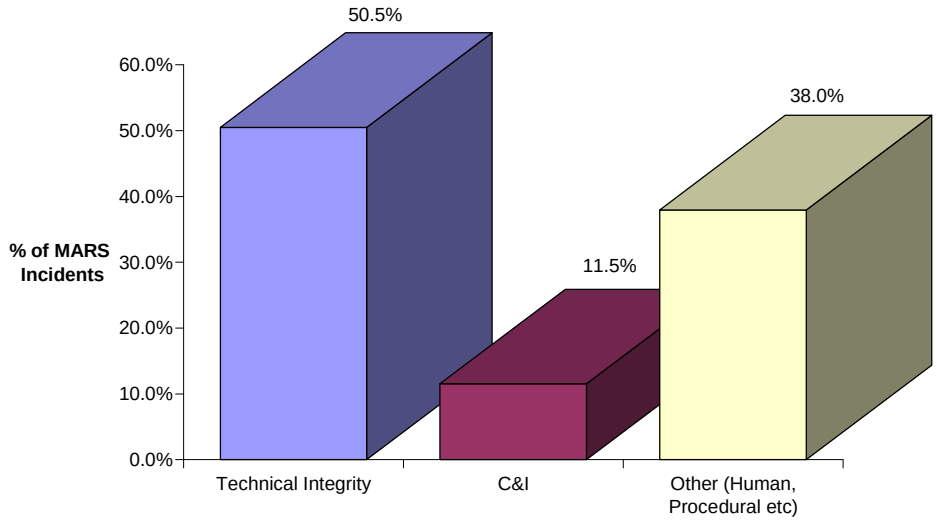


Figure 3: High Level Categorisation of MARS Incidents.

The Technical Integrity category is of particular interest to this study. The breakdown of causes of these incidents is illustrated on Figure 4.

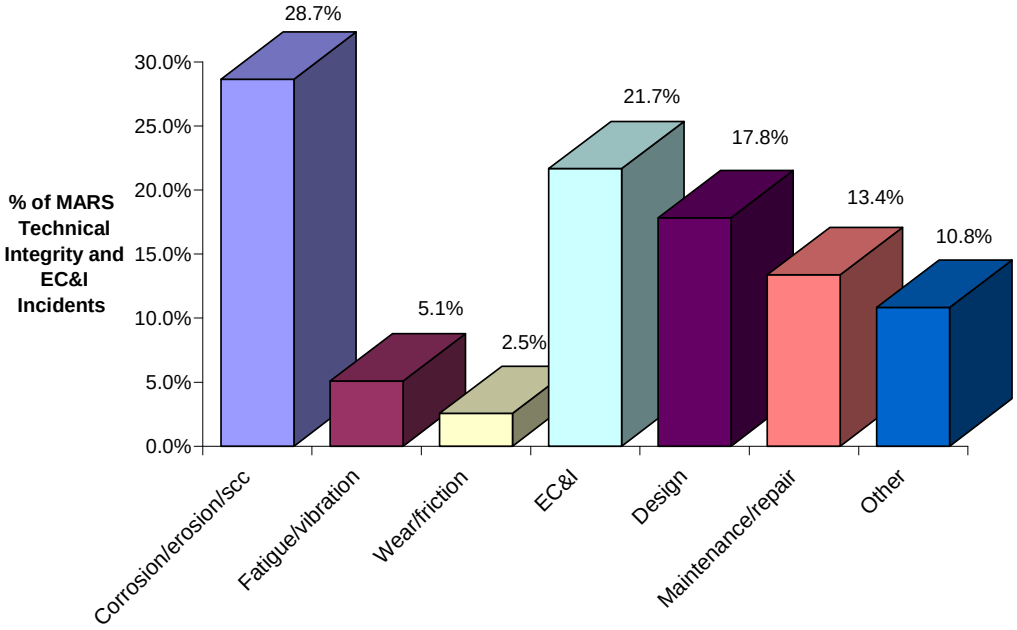


Figure 4: Causes of Technical Integrity Incidents in MARS data.

Combining these causes into those that can be identified as ageing issues leads to Figure 5.

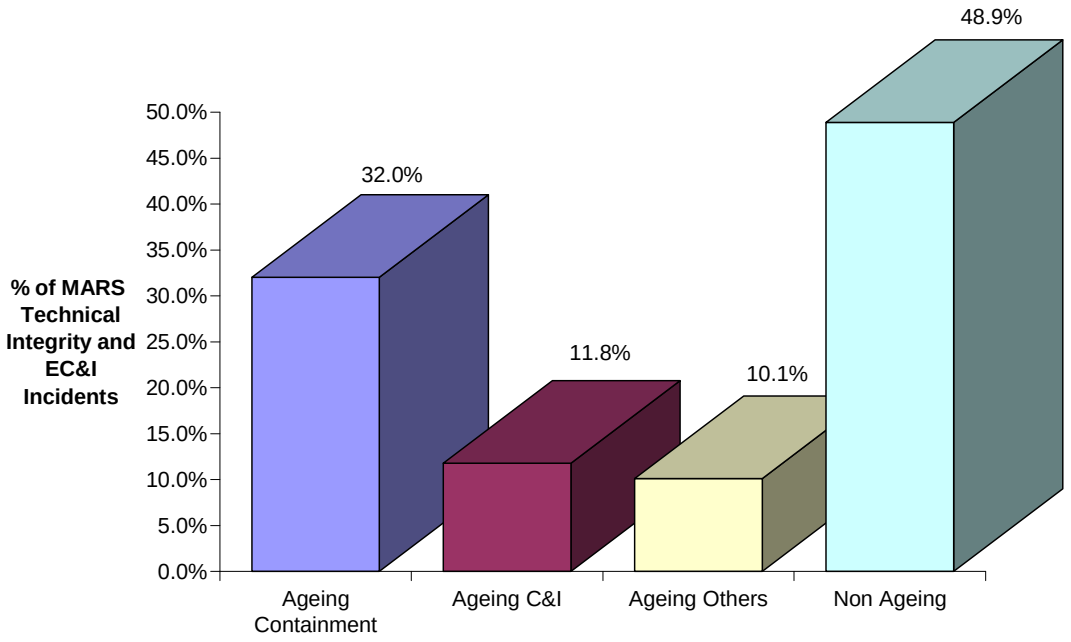


Figure 5: Proportion of MARS Incidents with Ageing as the Cause.

This analysis indicates that approximately 50% of Technical Integrity and EC&I related incidents are age related.

Given the uncertainties in the analysis a broad assessment of the size of the ageing problem may be made by the statement:

"60% of 'potential major accident' incidents are Technical Integrity or Control and Instrumentation related issues and 50% of those are associated with ageing of one type or another".

These findings are broadly in accordance with previous HSE research. For example 'Findings from Voluntary Reporting of Loss of Containment Incidents 2005/06' state that 50% of accidents are caused by incorrect operator action and 22% are caused by equipment/plant failure. Corresponding figures for 2004/05 are 37% operation and 32% plant failures. Although it should be noted that the HSE data reflects a wider range of loss of containment incidents, not just those of major accident potential from a COMAH / Seveso II site. For example, RIDDOR events could include smaller spills or leaks from maintenance operations or during operator sampling; these are unlikely to be reportable to MARS. Therefore it is to be expected that the MARS data may show a higher incidence of technical integrity failures compared to RIDDOR both due to the major hazard nature of the site, which should have well developed HSE management systems in place, and the focus of the MARS reporting arrangements on the larger leaks with a major accident potential.

The MARS database also provides estimates of the severity of the incidents in terms of their human, ecological and financial impacts. This information has been used to assess the impacts arising from ageing related incidents. The findings are summarised below.

Table 2: Deaths and Injuries statistics ([1] - one incident with 2242 injuries).

Class	Total	Deaths			Injuries		
	No. Incidents	Incidents	Total deaths	Deaths per Event	Incidents	Total injuries	Injuries per Event
All Events	348	57	124	2.2	140	4201[1]	30.0
(Excluding [1])					139	1959	14.1
All Integrity	149	11	35	3.2	51	768	15.1
Integrity ageing[2]	57	3	4	1.3	21	125	6.0
C&I ageing[3]	21	2	4	2.0	4	32	8.0
Other ageing[4]	23	2	3	1.5	7	47	6.7
All ageing[5]	96	7	11	1.6	30	183	6.1

Notes:
[2]- Ageing from corrosion, erosion, stress corrosion cracking, fatigue, corrosion fatigue, vibration and wear.
[3]- Ageing where C&I is a factor
[4]- Ageing from other sources (safeguards, structural, etc)
[5]- All ageing sources (5 incidents double counted from [2]-[4])

There are no numeric fields giving numbers of deaths and injuries. These have been extracted from the textual Short5Description field.

Table 3: Incidents involving ecological impact, material loss and community disruption.

Class	Total No.	Ecology Impact	Incidence of Ecology Impact	Material Loss	Incidence of Material Loss	Community Disruption	Incidence of Community Disruption
All Events	348	64	18%	224	64%	80	23%
All Integrity	149	26	17%	95	64%	37	25%
Integrity ageing	57	11	19%	35	61%	17	30%
C&I ageing	21	4	19%	10	48%	3	14%
Other ageing	23	4	17%	16	70%	3	13%
All ageing	96	18	19%	58	60%	23	24%

Table 4: Total losses (M ECU equivalent)).

Class	Total Losses (MECU)	Incidents where loss	Average Loss per Event (MECU) *	All Incidents	Average Loss per Event (MECU) *
All Events	794.7	107	7.4	348	2.3
All Integrity	329.1	42	7.8	149	2.2
Integrity ageing	149.7	18	8.3	57	2.6
C&I ageing	17.8	7	2.5	21	0.8
Other ageing	3.6	4	0.9	23	0.2
All ageing	171	28	6.1	96	1.8

Note * - this is the average loss across those events for which a loss was reported. Not all incidents reported an economic loss.

The average economic loss per ageing incident (averaged across all 96 ageing events) is 1.8 MECU. The highest average is the average for ageing related containment integrity failures at 2.6 MECU. This compares with the average loss across all MARS incidents (348 events) of 2.3 MECU.

These are the total losses for incidents, with losses quoted estimated from the relevant numeric fields and text fields in the 'Short5Description' data. The text fields contain many estimates not contained in the numeric fields and the numeric fields contain some data not referred to in the text fields. Furthermore, the numeric fields have some entries overestimated by an order of magnitude. These fields have been rationalised to give the data presented in Table 4.

From these tables we can conclude that ageing incidents are unremarkable with respect to deaths/injuries but when losses do occur, these have relatively high associated costs and impacts on local communities.

The relatively lower death and injury rates associated with integrity ageing incidents is thought to be due to the fact that many ageing incidents such as corrosion failures can occur at any time, so it is unlikely that people would be near the leak site at the time of the leak. This can be compared to events arising from say maintenance or operating errors where people would be present at the incident site. EC&I ageing incidents result in injury rates similar to the average.

The averaged cost impacts of 'ageing' incidents are shown to be slightly lower than for the 'average' incident. This may be due to the fact that some of these incidents may be localised and readily fixed. However, the average cost impact for ageing containment integrity incidents is higher than that for the 'average' incident. This probably reflects both the economic impact of the plant outage and repair costs of significant leaks, and the fact that some of the more serious leaks would have escalated, causing widespread damage to the plant. Major leaks and escalating events arising from containment failures may also explain the higher incidence of community impact associated with ageing events.

The following sections describe in more detail the current findings from the review including those from analysis of the RIDDOR and MHIDAS reports. The objective of these asset specific analyses is to establish the nature of the incidents rather than to try to refine the assessment of the potential size of the problem for the reasons given above.

4.4.2 Primary Containment Systems

There were sufficient numbers of reported incidents involving ageing of primary containment to produce graphical representations against the identified issues. The results are shown below.

The numbers of incidents in the various specific issues categories are shown on Figure 6.

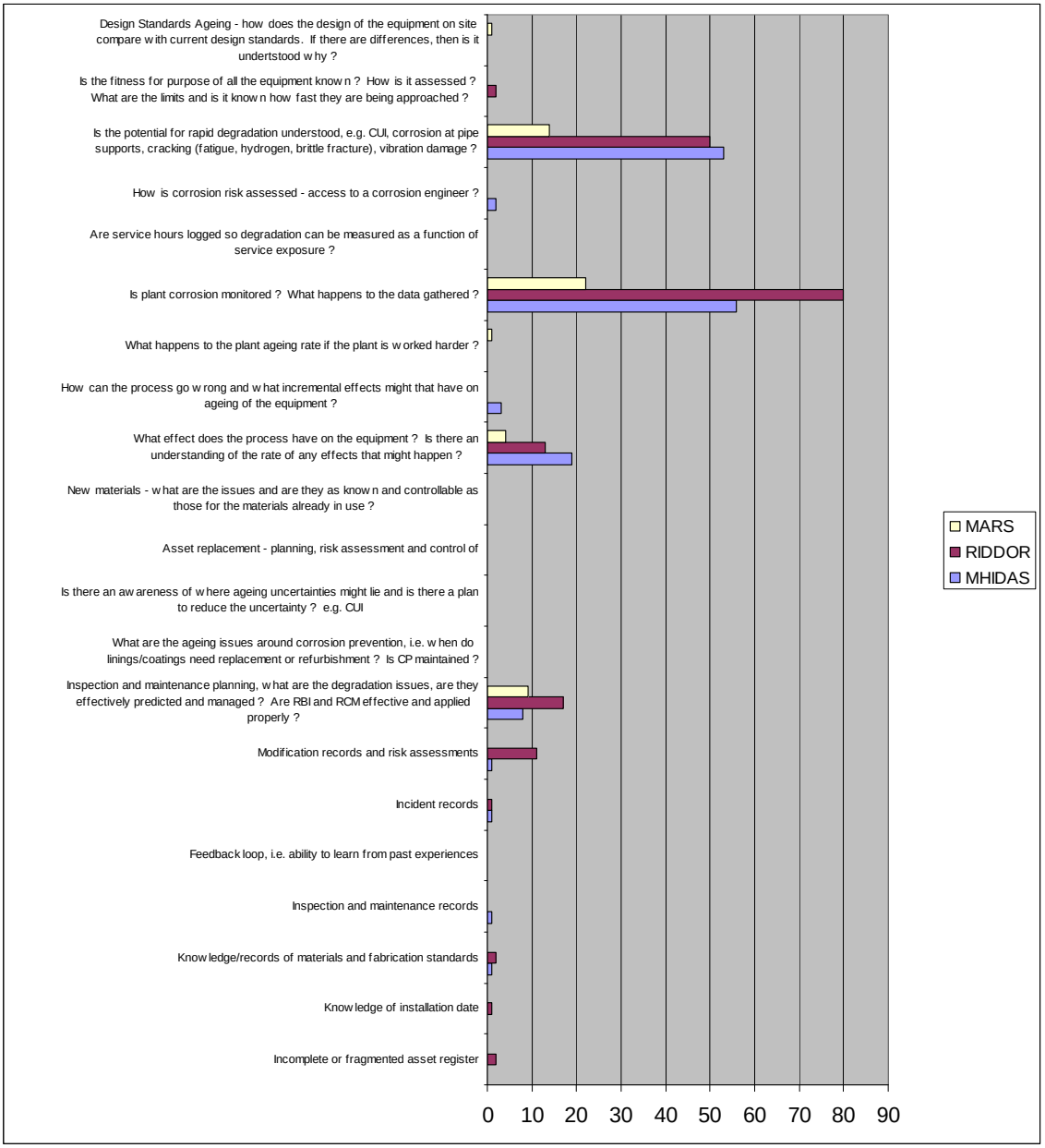


Figure 6: Number of Incident Reports attributed to Ageing Issue Categories (Primary Containment).

The fraction of incidents as a percentage of the total record numbers is shown on Figure 7.

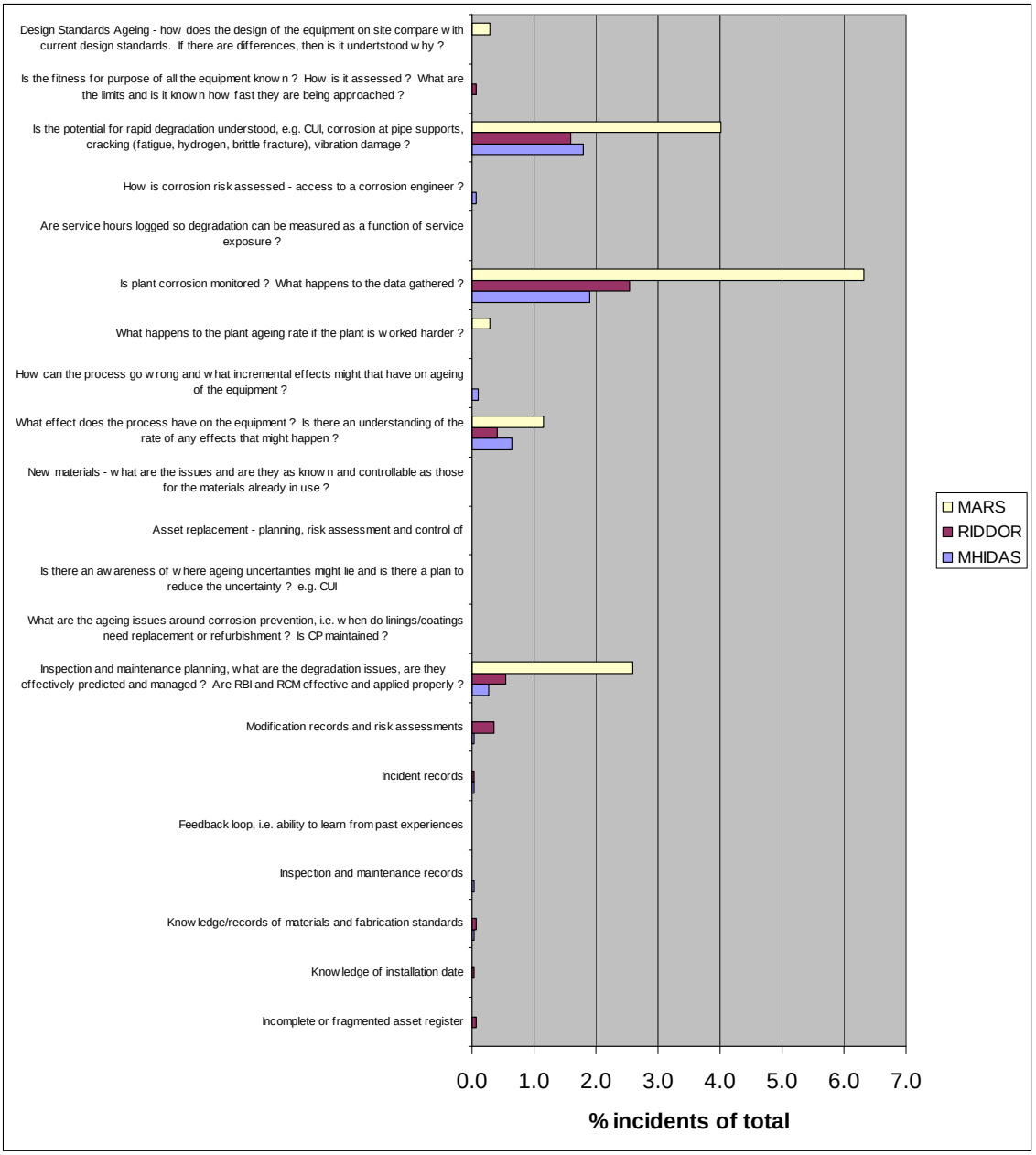


Figure 7: Fraction of Ageing Incidents (of the Total) per Issue Category (Primary Containment).

The proportion of incidents as a fraction of reports attributed to ageing for each data source is shown on Figure 8.

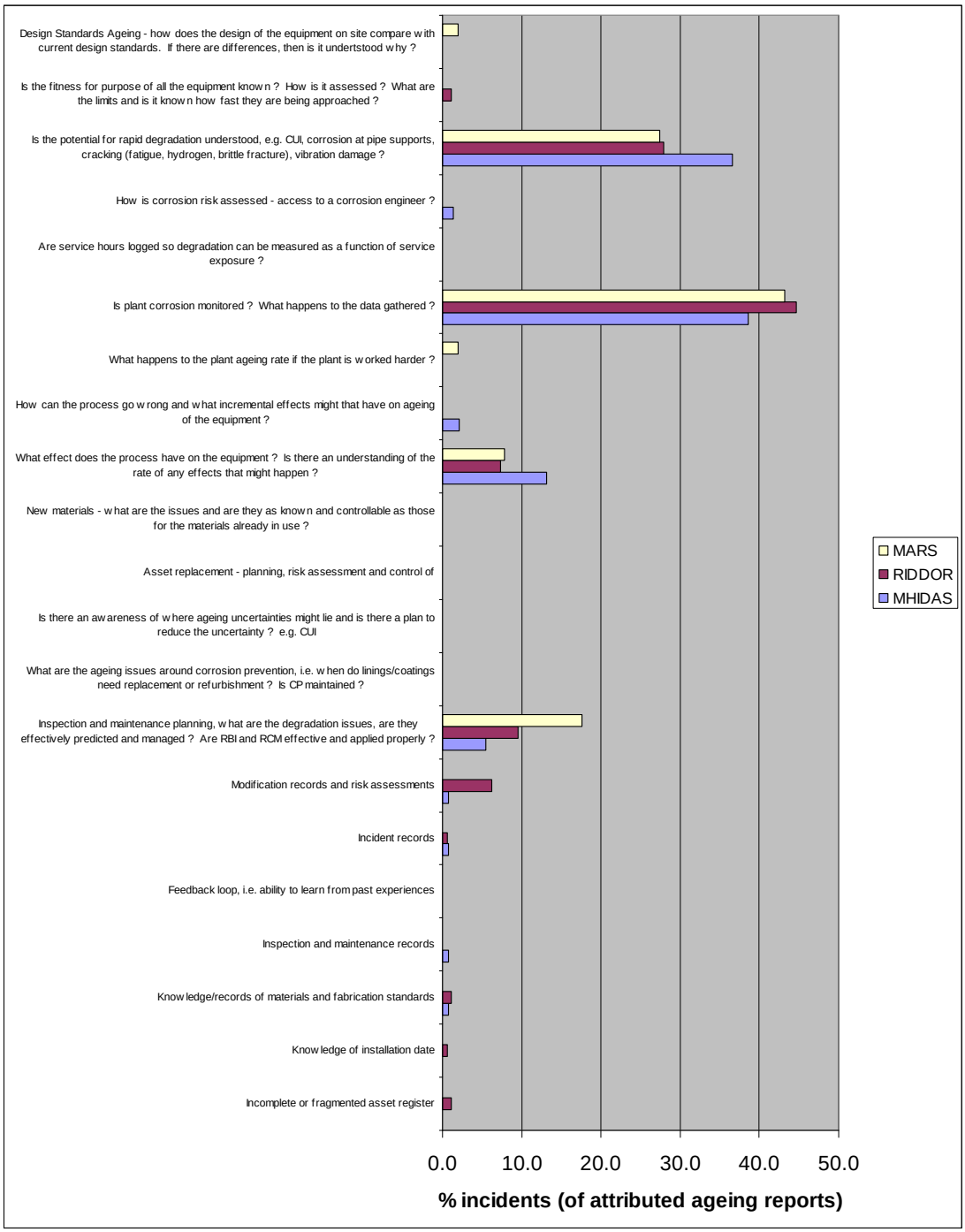


Figure 8: Proportion of Incidents as a Fraction of Attributed Ageing Reports (Primary Containment)).

Several observations can be made:

- The absolute number of incidents that can be directly attributable to plant ageing for primary containment systems is not insignificant. This is further focused by the observation from the MARS data that ageing issues appear to play a proportionately more significant role in major accidents when the reporting formats allow more positive identification.

- There is general consistency between the incident reporting systems on the specific issues that are leading to failures on plant. Furthermore, the proportion of incidents attributed to the specific issues within each database is in good agreement.

- Corrosion remains a significant issue.

- Failure mechanisms that can lead to rapid failure but are still significantly influenced by age, e.g. fatigue, stress corrosion cracking, CUI etc, are a significant issue.

- Planning of inspection and maintenance activities significantly influences the results, i.e. failure to plan for ageing issues is apparent in the databases.

- The effect of the process on plant ageing is not fully understood, i.e. changing the process or increasing throughput is not evaluated in terms of the effect on the ageing rate.

The following incident reports have been selected from the databases to illustrate some of the key findings of the primary containment systems review:

Lessons Learnt	**Corrosion management improvements required. Detection by smell unreliable in wet conditions.**
Data Source	**RIDDOR Loss of Containment Data**
HSE Case ID	**1879335**
Primary Cause of Incident	**Corrosion**
Description of Incident	**50 - 65 tonnes Dibromoethane lost to bund from pin hole leak in transfer pipework. Dibromoethane (DBE) is used as an additive to Motor Fuel Anti-Knock (MFAK) compounds. It is stored on site in dedicated tanks within a building will dual ROVs in series on each outlet line. One for process control (actuated from within storage building) and one for emergency shut down. DBE is delivered by road tanker and drawn off to the blending operations in a separate building 20-30m distant by staff located there. DBE pipework is generally of high spec. steel but still it is liable to create pin holes & leak. Leaks are usually rapidly detected by means of the distinctive smell while the loss of containment is still very small. Routine checks of pipework were employed. Previous experience has led the operator to replace the majority of this pipework with PTFE-lined pipes. Use of DBE has reduced in recent years. Originally the plant employed 4 tanks. 2 in an external bund and 2 within a building. The former are not now used, but the delivery pipework at the time of the incident ran from the storage building through the external bund before reaching the transfer pumps in a small room attached to the storage building. When the majority of transfer pipework was replaced, that from the tanks running through the bund to pumps was not replaced. It was expected that leaks would be rapidly detected and loss would be into the bund & hence controlled. This leak began as a pinhole in a jacketed reduction piece in the line which was at the rear of the bund against a wall. The pipe was approx 8 inches from**

	the floor of the bund. However at the time of the leak there was rain water covering the bottom of the bund. The leaking DBE fell approx 3 inches and was contained under the surface of the water, preventing detection by smell. As the leak progressed, the hole in the pipe increased in size to a final 20mm diameter.
Risk Control System	**Inspection.**

Lessons Learnt	**Need for:** **Increased temperature monitoring and valve performance on all boilers & furnaces to identify operational control concerns.** **Introduction of weekly manual review of attemperator, desuperheater & letdown station valve performance with view to developing online system.** **Review of process areas with potential to involve similar failure mechanisms** **Review of maintenance strategy for control valves** **Review of boiler inspection strategy to determine implications of failure.**
Data Source	**RIDDOR Loss of Containment Data**
HSE Case ID	**4119823**
Primary Cause of Incident	**Thermal Fatigue**
Description of Incident	**During normal site operation a 6 inch longitudinal crack appeared on the Super High Pressure (SHP) steam line downstream of the second stage attemporator valve of Boiler A. This caused an escape of SHP steam. The boiler was safely shutdown. There were no injuries. Metallurgical analysis suggests thermal fatigue rupture which is supported by examination of operating data trends for last 2 months which indicated fluctuating water control leading to variable temperatures (35oC swing, measured 11m downstream of valve). On examination of the valve, the feedback arm was found to be damaged which would lead to poor valve control. The spring pre tensioner on the actuator had unwound and relieved all load on the spring causing the valve to malfunction. Indications of cracking on valve seat indicate fatigue failure at this location. An examination of the maintenance history by the Co., showed the valve had no history of this failure mechanism. Internal erosion resulted in the valve body being replaced in 2005, reused same actuator. Preliminary findings suggest valve actuator and feedback arm failure resulted in erratic valve control and poor water distribution in the line, which lead to thermal fatigue of pipework (failure location of pipe was 1400mm from water injection point) because of fluctuating local**

	overheating/cooling on the line downstream of the valve.
Risk Control System	**Process monitoring/RBI/Inspection & Maintenance**

Lessons Learnt	**Improve inspection planning, improve incident response training**
Data Source	**RIDDOR Loss of Containment Data**
HSE Case ID	**1880828**
Primary Cause of Incident	**Failure to plan and conduct inspections**
Description of Incident	**SO2 emissions from sulphuric acid plant during plant start up affecting contractors on on- site construction project. Failure of catalyst beds in sulphuric acid plant led to incomplete conversion of SO2 in converter. Cloud of SO2 in high concentration released from stack. Still significant concentrations of SO2 when cloud reached ground level at adjacent construction project. Contractor employees reported symptoms of exposure to SO2. Taken to hospital for checks then released. Peak levels of SO2 of up to 10ppm measured at one point on construction site. Firm's own fault tree analysis points to poor siting of construction project, poor inspection & maintenance of acid plant and inadequate operator response to high SO2 levels in process stream due to failure to appreciate their safety significance pointing to inadequate training & poor communication.**
Risk Control System	**RBI/Inspection & Maintenance/Incident Response**

Lessons Learnt	**Improve RBI and take account of current standards**
Data Source	**MARS**
Case ID	**-**
Primary Cause of Incident	**Inappropriate corrosion rate prediction in RBI scheme.**
Description of Incident	**Corrosion of vessel floor resulting in hole approx 20cm2. Oil sand base to tank was washed out by escaping oil. Company had anticipated pin hole leaks would appear. Failed to determine extent of pitting corrosion or its rate of progression. Vessel was inspected in 1991 and new steel floor inserted during tank "rehabilitation" in that year Company working to "Risk Based Inspection" regime concluded that next inspection should be in 2001 on basis that at predicted rate of corrosion, only pinholes leaks would appear prior to that date. Predicted that such pinholes would result only in slight seepage, controllable by injection of water to base of tank. In event, tank failed much more aggressively and quickly, resulting in rapid loss of crude oil to bund. Corrosion rate calcs and corrosion management reviewed against international standards and made more demanding eg revision of metal thickness retirement criteria.**
Risk Control System	**RBI in conjunction with current standards.**

Lessons Learnt	Fully assess process changes.
Data Source	MARS
Case ID	-
Primary Cause of Incident	Process change.
Description of Incident	Since 1980 plant operated with 4 x SO3 storage tanks feeding reactors. In August 1992 following HAZOP of tanker offloading operation Tank no. 2) was modified to be a vent/dump tank, ie tank kept empty but used to vent off excess air pressure in delivery tankers and be available for emergency dump of tanker/tank of SO3. As tank no longer used for transfer storage pump removed (July 93) and temp gauge removed (June 95). Resulted in tank temp being reduced to about 25C and no regular visual checks on contents. Incident occurred during shutdown for maintenance including clean out and internal inspection. No purge or visual checks made prior to addition of water to wash out tank on assumption it was empty, but 3.5 te SO3 (probably solid polymer) had built up inside. Procedures for assessing plant/ process changes not applied adequately in respect of key changes over previous 4 years- led to unexpected build up of SO3 in vent/ dump tank. Lack of adequate procedure for tank clean out and failure to apply non-routine job procedure led to addition of water to tank before SO3 removed.
Risk Control System	MoC Procedures

HSE Research Report RR509 on Plant Ageing[4] provides descriptions of some of the types of damage that lead to the incidents identified in the databases. These descriptions are reproduced below for convenience[5].

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. 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) **Wall thinning** may occur due to:

[4] HSE Research Report RR509, Plant Ageing – Management of Equipment Containing Hazardous Fluids or Pressure, 2006.
[5] This study does not seek to duplicate the work reported in RR509 but rather to build on it by identifying key elements of RR509 that relate directly to the types of ageing phenomena identified in this review.

- *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.

(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.
- *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.

(e) **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.

Additionally RR509 provides a very useful overview table (shown here as Table 5) describing indicators of ageing of the types identified for primary containment systems.

Table 5: Indicators 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 the later stages of its life. 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.

Phase 2 of this study will develop questions of use to HSE Inspectors based on the observations from the database review and the useful guidance provided in RR509. However, at this stage it is possible to suggest some basic questions based on the findings of the review and the relevant information in RR509:

1. Are age-related damage mechanisms identified and assessed in the plant inspection and maintenance plans?

2. Are appropriate inspection and maintenance techniques applied that are effective in management of age-related degradation?

3. Is corrosion, both internal and external, monitored and trended? How are the results of the monitoring used to influence future integrity management actions?

4. Is the potential for cracking understood? Do justifications exist for planned actions, or lack thereof, to manage cracking?

5. Are changes to the process assessed in respect of impact on plant integrity over short, medium and long terms?

6. Does the installed equipment meet the requirements of modern design standards? If not, are the key differences between the original standard and its modern equivalent understood and the potential impact for plant integrity assessed?

4.4.2.1 Equipment Manufactured from Non-Metallic Materials

It should be noted that some primary containment equipment is manufactured from non-metallic materials. RR509 touches on these and the general principles still apply. However, there is a perception within industry that such materials are not susceptible to age related degradations. This section examines this type of equipment specifically in order to determine whether or not there is a need for a different approach to management of ageing.

The RIDDOR database contains one example of failure of a GRP tank (Case ID 1041819) but unfortunately no details are provided concerning the failure mode.

Composite materials have been used in chemical, processing and refinery applications for close to 40 years primarily in containment applications. The benefits are their perceived corrosion resistance and good strength to weight characteristics. The composite materials used in this industry is primarily glass fibre reinforced plastic (GRP). A variety of glass fibre types and resins may be used dependent on environmental and conditions.

Composites are tolerant materials and providing the correct resin and fibre types have been selected and the components are properly installed few issues are normally encountered in service. Particular problems can be encountered with adhesive joints. Material selection in corrosive environments is a specialist area and end users are reliant on service experience and advice and ratings supplied by the main composite suppliers.

In chemical and processing applications, pressure vessels and piping are often lined with polyethylene or other resistant polymers. Commercial grade composites in these industries are normally produced by filament winding, with increased use of moulding process such as resin transfer moulding (RTM). Manual overlay, lamination or moulding is used on filament wound pipe in the tapered regions associated with nozzles, flanges, manifolds and attachments.

<u>Non-Metallic Materials Issues</u>

Composites do not corrode per se but can be subject to a number of degradation mechanisms in-service including physical ageing, mechanical ageing and chemical ageing. The consequence of these can be a reduction of 20 - 40% or greater in the strength characteristics of the polymer during the lifetime of the component and introduction of damage including matrix cracking and delaminations. This is handled in design codes by use of regression curves based on short term and longer term (typically 1000h) tests to determine the *qualification pressure* for the component and the allowed *operating pressure* over the design life..

There is concern about whether such methods of life assessment are sufficiently robust, given the increasing diversity of applications in which composites are applied. In contrast to steel vessels or pipework where non-destructive methods such as ultrasonics, electromagnetics and radiography are widely applied, very little inspection other than visual

inspection or pressure testing is currently undertaken on composite components in the chemical, process and petrochemical industries.

There are limitations in the testing methods used to estimate the regression curve or degradation that may occur with ageing in service. Most studies are in water rather than organic solvents or the other fluids that are seen in service. Immersion testing rather than single-sided exposure mechanisms may cause mass gain as well as loss; so single-point data of limited use in prediction of longer term degradation. Service components suffer environmental degradation from the surfaces; hence the degradation seen in immersion tests may be worse than seen in practice.

Most ageing studies accelerate ageing by testing for a shorter time (~1000h) at a more elevated temperature. Small temperature increases above the service temperature but below the resin's glass transition temperature can offer useful indications of long term behaviour. However if the mechanisms encountered over the longer term differ to those in the accelerated tests, the degradation curves and predictions of remnant life obtained may be unrepresentative.

A diversity of environments can be encountered in the chemical and process industries. These can cause damage to both matrix and the fibres. It is important that the resin and fibre types are correctly selected for the application to maximize the resistance in service. In oil industry applications a corrosion resistant layer (or veil) containing more resistant fibres and gelcoat is commonly applied to the surface. Similar practice may be used in chemical applications. Such layers are effective at preventing environmental damage but are relatively thin (~200um). It is important to confirm on visual inspections that excessive grazing of the gel coat has not occurred and that damage has not occurred to these protective layers

Areas of bend, variations in thickness, support or change in geometry are particularly susceptible to damage or degradation in composite systems. These may encounter local stress concentrations and care is needed in design to ensure these can adequately support the operating pressures of the piping or vessel and that the allowance made in regression curves for ageing is sufficient.

There are particular issues for lined or painted GRE vessels or pipework. If a lining is used then a compromise may be made on the resin and fibres used in the GRE vessel. These may not be as resistant as would be used if the GRE was exposed to the environment. It is important in this case to monitor the lining condition since lining failure could lead to degradation and failure of the GRE vessel in a shorter timescale than might typically occur for an unlined vessel exposed to the same environment. Composite components are often painted for cosmetic reasons. This may provide some additional protection to the external environment. A consequence is that it is no longer possible to inspect the component visually using internal illumination, a standard method. In this case detection and monitoring of service damage may be more difficult..

In the onshore and offshore oil and gas industries a more robust approach is developing[6] based on materials characterization and non destructive evaluation of the actual damage in service components. This offers to improve the accuracy of life prediction and reduce the risk of premature failure. There would be benefits in extending such good practice more widely in the chemical and process industries.

A more detailed description of the types of failure mode observed in non-metallic materials in containment service is provided in Appendix 2.

[6] Ageing of composites in oil and gas applications, S Frost; Ageing of Composites, Ed. Rod Martin, Chapter 14 p 375-395, Woodhead publishing, ISBN 978-1-84569-352-7, 2008

Considering the identified issues for non-metallic materials the questions raised in Section 4.4.2 are applicable. However, some additional questions may be required to cover all potential applications for these types of materials, specifically when they are used in repair procedures for failed or failing metallic components. Consideration will be given to this during Phase 2 of the study.

4.4.3 EC&I Systems

4.4.3.1 EC&I-related accidents and other incidents

There is a very large body of case studies involving EC&I failures. A very brief description of a small selection of interesting and relevant accidents and incidents is presented in Appendix 3 that includes;

- Details of the EC&I aspects of the Buncefield, Texas City and Ariane 5 accidents.
- Details of some incidents which were of minor consequence but which could potentially have been significant in different circumstances.

Further case studies of EC&I related failure will be included in the Phase 2 report.

4.4.3.2 Analysis of data from accident databases

The objective was to try to identify general conclusions from a large quantity of data within the RIDDOR, MHIDAS and MARS databases:-

1. Keyword searching is available but is of limited value since the databases describe a large number of accidents at widely-differing plants, sometimes using different expressions to say similar things, e.g. “concentration meter” or “gas analyser”, etc.
2. In some cases there are multiple entries for a single incident.
3. While a variety of causes may be given in the databases, the genuine root causes are often not clear, and it is necessary to ‘interpret’ the available information.

The following general comments can be made:

1. For many faults, it is often difficult to tell from the databases whether faults were due to ageing plant or just poor maintenance.
2. It is likely that EC&I aspects get under-reported, e.g. a failure can be ascribed to “overpressure” without it being clear whether this was due to a control problem.
3. For all three primary data sources there was insufficient data to form a meaningful statistical view due to large uncertainties in reporting. Positive identification of EC&I ageing issues proved difficult and was subject to a degree of judgement. Consequently no attempt has been made to characterise incidents in terms of the

specific identified EC&I issues at this stage and a general description of the review findings is considered to be more informative.

RIDDOR Data Review

An analysis of RIDDOR loss of containment accidents where Electrical, Control and Instrumentation issues were a significant factor has been conducted. To summarise the analysis:

- EC&I issues were associated with 36 out of 3143 loss of containment accidents, just over 1%.
- Almost 60% of EC&I issues were associated with Maintenance, one third were associated with Design.
- Over 30% of issues were associated with level detection, of these 90% are associated with maintenance.
- Other significant issues include Loss of Site Power, Software failures and problems with upgrading old control systems.

In considering ageing, because of the limitations of the data provided, it was not possible in every case to definitively classify EC&I issues as ageing or otherwise. However, the following analysis could be inferred;

Table 6: RIDDOR EC&I Analysis.

Ageing Classification	Number	Percentage of EC&I accidents	Percentage of all accidents
Not Ageing (No)	24		
Possibly Ageing (?)	7		
Ageing	3		
Aged	2		
Total EC&I issues	36		
Possible Ageing EC&I	12	33%	0.4%

From this it can be seen that up to one third of the EC&I incidents may be associated with ageing. On this basis up to 0.4% of all incidents may be associated with ageing EC&I.

MARS Data Review

An analysis of MARS incidents where Electrical, Control and Instrumentation issues were a significant factor has been conducted. To summarise the analysis:

- EC&I issues were associated with 34 out of 348 accidents, 10%.
- 44% of EC&I issues were associated with Maintenance, 26% were associated with Design.
- 15% of the issues were associated with level detection, all associated with maintenance.
- Other significant issues include Loss of Site Power and Software failures, including problems with upgrading to new DCS.

In considering ageing, because of the limitations of the data provided, it was not possible in every case to definitively classify EC&I issues as ageing or otherwise. However, the following analysis could be inferred;

Table 7: MARS EC&I Analysis.

Ageing Classification	Number	Percentage of EC&I accidents	Percentage of all accidents
Not Ageing (No)	13		
Possibly Ageing (?)	17		
Ageing	4		
Aged	0		
Total EC&I issues	34		
Possible Ageing EC&I	21	62%	6%

From this it can be seen that up to around 60% of EC&I related incidents may be associated with ageing. On this basis up to 6% of all MARS incidents may be associated with ageing EC&I.

MHIDAS Review

It is clear from the databases that most incidents can be ascribed to a number of causes. Root cause analysis is not available. However the apparent causes of all the accidents and incidents in the MHIDAS database which assign “instrument” or “control”, and “electric” or “lightning” as *general* or *specific* causes can be analysed as shown in the table below.

Table 8: MHIDAS EC&I Analysis.

Apparent Cause	Number
Level instrumentation	7
Earth bonding or faulty EX equipment	1
Electrical supply failures	43
Lightning strike	16
DCS problems	11
ESD	4
Override of installed interlocks	1
PTW	1
Operating procedures	3
Other (specific instrument problems)	13
Total	**100**

In considering Electrical failures only, the following issues were significant:

60 out of 2951 recorded accidents (2%) where electrical supply issues or lightning strike was a significant factor		
Lightning	16	27%
Power supply interruption	43	72%
Earth bonding or faulty EX equipment	1	1%
Total	**60**	

Electrical supply failures and lightning strikes are frequently cited as initiating events. However, it would be expected, in well-designed plants, that other failures would be necessary for an accident to occur. Such explanation is usually missing in the reports in the databases.

A further keyword search including free text fields was undertaken to identify Electrical, Control and Instrumentation issues. In summary:

59 out of 2951 recorded process industry accidents (2%) where EC&I a significant factor.
Unable to identify ageing issues without further data, however, key themes are;

Sensor functional failure *(of which 7 were level instrumentation)*	18	31%
Control system malfunction	13	22%
Sensor integrity failure - leak	5	8%
Power failure	2	3%
Others	4	7%
Unassigned EC&I causes	17	29%
Total	**59**	

In considering the risk control failings of the Electrical, Control and Instrumentation issues:

- 67% of EC&I accidents caused by maintenance shortcomings
- Next significant is Control failures (including software) at 15%
- Level detection associated with over 20% of accidents - all of which caused by inadequate maintenance

General Observations

General observations from the EC&I accident data analysis are;

1. EC&I issues are a significant factor in around 2% of major accidents (RIDDOR 1%, MARS 10%, MHIDAS 2%).

2. EC&I accidents that could have been prevented by improved maintenance and testing represent a significant percentage of all accidents caused by EC&I issues (RIDDOR 60%, MARS 44%, MHIDAS 67%).

3. The biggest single factor in all EC&I failures is associated with Level Detection, often resulting in vessel overfill and loss of containment (RIDDOR 30%, MARS 15%, MHIDAS 20%). The vast majority of these failures are associated with inadequate maintenance and testing.

4. Design issues account for a significant proportion of EC&I associated failures (RIDDOR 33%, MARS 26%, MHIDAS 30%) – although these are not usually associated with ageing issues.

5. Other significant causes of EC&I failure include Loss of Site Power, Lightning/Earthing and Software failures, including examples of issues caused during upgrading to modern DCS control systems.

EC&I Incident Examples

The following examples of Ageing Plant Electrical, Control and Instrumentation issues are highlighted;

Lessons Learnt	All safety critical instruments need to be identified and appropriate maintenance and testing must be carried out to ensure that interlocks are available when required.
Data Source	RIDDOR Loss of Containment Data
HSE Case ID	4065244
Primary Cause of Incident	Ageing of safety critical level instrument.
Description of Incident	A high level switch failed resulting in the interlock on the inlet valve failing to close during a tank filling operation. The tank over-filled and approximately 600 kg of flammable product was released into the bund. The tank was fitted with a high level float switch that failed due to a hole in the float caused by corrosion or old age.
Risk Control System	Identification of safety critical instruments. Periodic maintenance and testing of safety critical instruments.

Lessons Learnt	Obsolete plant control systems need to be replaced in a planned and systematic manner.
Data Source	RIDDOR Loss of Containment Data
HSE Case ID	1882968
Primary Cause of Incident	Ageing of plant control system
Description of Incident	Release of flammable liquid from overfilled crystallisation vessel. The company had long acknowledged that the Ferranti DDC process computer had problems and were planning to replace it with a Rosemount DCS system. The lessons learned from this incident will be incorporated into the new system ie. "plain English" text announcing and identifying alarms, "tiering" of alarms to assess their importance.
Risk Control System	Planned project to upgrade plant control system.

Lessons Learnt	Arrangements must be made to manage loss of site electrical power.
Data Source	RIDDOR Loss of Containment Data
HSE Case ID	1880741
Primary Cause of Incident	Loss of site power
Description of Incident	Flare fire. Failure of electrical supply due to capacitor failure. Plant power dips and shutdown caused upset on all process plant. South side plant caused high levels in associated flare and subsequent overspill which ignited. Deficiencies in instrumentation, software, operator actions, and knock out pot hardware, all contributed to the incident.
Risk Control System	Emergency arrangements for loss of site power.

General Conclusions for EC&I equipment from Accident Data Review

1. There is a need, on all high-hazard plants, for very firm links between:

(i) the Safety Case (identifying the Safety Critical Elements)

and

(ii) the Maintenance Inspection and Test (MIT) schedule (taking each and every SCE and going right down to individual instruments, logic elements and output devices, also addressing potential initiating events like loss of supplies and lightning strike, and defining specific test requirements and frequencies).

2. The MIT schedule, based on the Safety Case, needs to be matched with KPIs measuring the backlog of safety-related maintenance, to make sure that management can see that the appropriate MIT work is being completed.

3. All high-hazard plants should include in their safety cases a clear demonstration that:

(i) the design has considered safety implications of loss of electrical supplies (both locally and site-wide)
(ii) there is adequate lightning protection (which is maintained adequately),
(iii) the single failure criterion has been taken into account.

4.4.3.3 EC&I Ageing Issues

A Site Inspector, on entering a Hazardous Installation for the first time, will have to form judgments (based on observations and discussions with staff) on certain key themes, as follows:

1. Is the EC&I equipment “ageing”?
2. Do the Operators understand the safety significance of their EC&I equipment?
3. Are the Operators planning for the likely replacement of at least some of the EC&I equipment during the lifetime of the whole plant? Are they aware of the technical and resource issues?
4. Are the Operators aware of issues surrounding safety and “cost of ownership” of modern digital safety-related equipment?

5. Do the Operators have adequate arrangements for Maintenance and Procurement of modern EC&I equipment?
6. Do the Operators have adequate arrangements for Management of Change (MoC) when replacing older (typically analogue) EC&I equipment with new (almost always digital) equipment? This includes:
    - The MoC process itself,
    - Functional Safety Management (FSM),
    - Safety Integrity Level (SIL) qualification,
    - Software Verification and Validation (V&V),
    - Software configuration management, and
    - Project management

A further report (Phase 2) will address the issues in finer detail and will be presented in tabular format. These detailed issues will be addressed at a level which should enable the Site Inspector to challenge specialists employed by Operators and Duty Holders at an appropriate level.

Much of the EC&I 'problem' relates to the replacement of older analogue equipment with modern digital equipment. Software systems are not readily amenable to inspection and testing in the same way as older analogue equipment. Hence the procurement of new digital equipment for safety-related applications – to replace ageing analogue EC&I - requires particular effort, engagement, skills and resources from the operators.

4.4.3.4 What is "ageing EC&I equipment"?

There is no precise definition for "ageing EC&I equipment".

A textbook definition would relate to equipment which is approaching the right hand side of the reliability "bathtub curve". However, the change from random failure rates (i.e. the flat portion of the bathtub) to accelerating failure rates will differ for different types of EC&I equipment, and for different environmental conditions.

With care, even quite sophisticated EC&I equipment can be kept working to a remarkable age[7]. Other equipment may need replacing after quite short timescales. Modern digital equipment shows a tendency to have significantly shorter lifecycles.

EC&I equipment life can be extended if good support arrangements are in place either from the OEM or a specialist contractor. However, in general, the following principles apply:

- EC&I obsolescence is usually ultimately driven by spares availability.
- Most older EC&I equipment will be analogue.
- Almost all new equipment is digital.
- Demonstrating the safety of new digital equipment requires significant effort.
- Documentation and records need to be kept up-to-date, e.g. 'as built' drawings and specifications, change records, test records, etc as part of the demonstration that the equipment is still fit for purpose.

The capability to assure the safety of new digital equipment is therefore a key factor in managing the obsolescence of older EC&I equipment.

[7] The author is aware (2008) of an early DCS, using Ferranti Argus 500 computers with 32k ferrite core memories, which is approaching its 40th year. A project for its replacement is underway.

Cable ageing is dependent upon the type of cable (e.g. whether or not it is armoured), the type of insulation (e.g. some types of insulation degrade more rapidly when exposed to sunlight), the potential for mechanical or thermal damage, and humidity. Well-specified cabling can survive for twenty years or more outdoors and for years or more indoors.

Degradation and failure mechanisms of HV equipment (transformers, motors, generators, switchgear, etc) and techniques for their condition monitoring, will be discussed in the Phase 2 Report.

4.4.3.5 Why are digital systems difficult in safety-related applications?

The "problem" with the use of digital equipment for safety-related applications can be summarised thus: *Software systems are not readily amenable to inspection and testing in the same way as older analogue equipment.*

- Software-based systems can contain surprises which can have unanticipated side-effects.
- The risk of complete system failure may be greater than with analogue systems.
- Microprocessor-based control systems will have a large number of inputs and outputs all connected to a single decision-making element (the microprocessor itself). With analogue technology, both positive testing (*confirming that a set of input states produces the correct output states*) and negative testing (*confirming that a set of input states does not produce any incorrect output states*) are practicable because there are discrete logic elements. However, with digital technology, the large number of inputs and outputs connected to a single logic element means that negative testing is seldom practicable.

Hence the procurement of new digital equipment for safety-related applications requires effort, engagement, skills and resources from the operators.

4.4.3.6 Basic Information Requirements and EC&I Safety Principles

A Site Inspector may have to know certain basic information before he can make judgments about whether any particular site has problems regarding EC&I equipment. These basic information needs are categorised as follows:

1. Basic information on installed EC&I systems *(What type of equipment is there currently on site?)*
2. EC&I lifecycle issues *(What is the typical lifecycle of EC&I equipment? What ageing processes are there? What are the potential business impacts of large refurbishment projects? Can ageing be mitigated?)*
3. Safety aspects of modern digital equipment *(What are the key safety issues with modern digital equipment?)*

Basic information on the design and safety case of the installed EC&I

A list of 7 basic issues regarding the design and safety case aspects of EC&I equipment is presented below. The operators of COMAH top tier and lower tier sites should be able to answer these questions without undue difficulty.

1. What types of EC&I equipment are used at the installation?

2. Has the operator a full understanding of the significance of their EC&I systems in:

   (i) immediate process safety such as shutdown systems,
   (ii) process control
   (iii) mitigation of accidents
   (iv) monitoring plant for potential safety-related deterioration (process condition monitoring)?

3. Have all existing EC&I systems been assessed for their required SIL level? Are the operators aware whether the existing (ageing) EC&I systems meet these required SIL levels?

4. Are the operators aware of potential safety- and business-critical failure modes?

5. Failure to safety

6. EC&I Common-Mode Failure concerns

7. Arrangements for loss of site electrical power

EC&I lifecycle issues

The lifecycle describes the history of equipment from concept and specification through to decommissioning. A typical lifecycle, which includes EC&I equipment, is shown in Figure 9.

Operators should recognise that their EC&I systems will very likely need refurbishment or replacement during the overall life if the plant. Do they have a plan for this?

Operators should recognise that EC&I equipment is normally designed for replacement during the overall plant lifetime, and that EC&I equipment life is frequently determined by spares availability.

Operators should be aware of some key ageing processes for electronic components and also (importantly) for cabling. Also, some mitigation of ageing is possible in certain circumstances, e.g. by use of improved air conditioning for old DCS equipment.

Operators should be aware that major refurbishment projects – for example to replace a DCS – can have major business impact. This can be mitigated by a project strategy which replaces the peripherals on a piecemeal basis, although obsolete connections or protocols can present difficulties.

Migration of software from old to new equipment is a difficult proposition which requires care in planning and execution.

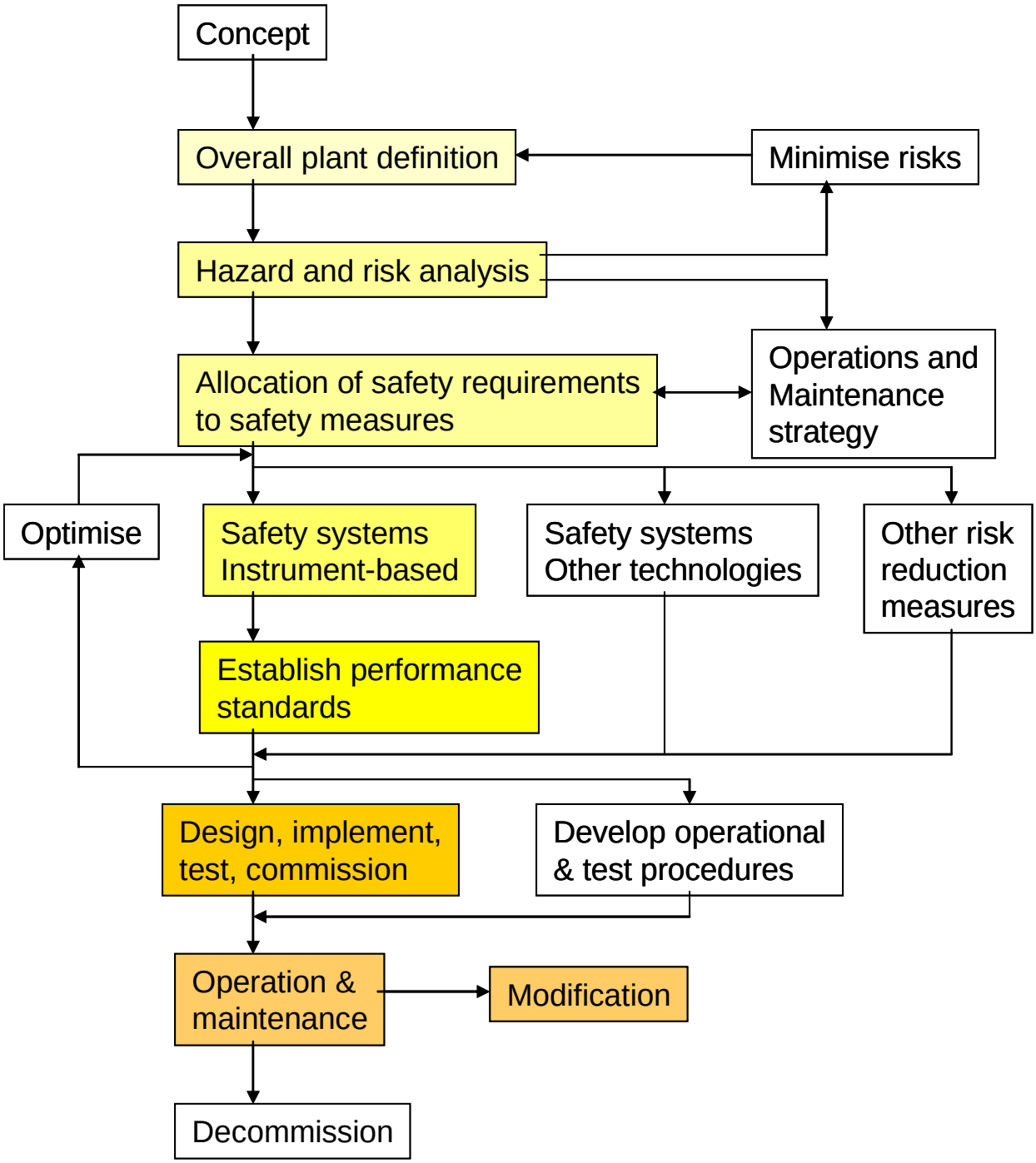


Figure 9: Safety Lifecycle.

(adapted from UKOOA, *Guidelines for Instrument-Based Protective Systems*, Issue 2, November 1999)

Some important safety aspects of modern digital equipment

Modern digital equipment has a significant 'cost of ownership'. Operators need to be aware of certain key issues which can affect the safety of digital equipment. These issues require resources (both human and financial) to ensure that digital equipment in high-hazard plants is specified, tested, commissioned and maintained properly.

So-called 'Smart' sensors and other COTS (Commercial-Off-The-Shelf) software-based equipment contain embedded software for signal processing and other functions. Software errors may affect the safe use of the equipment. 'Black box 'V&V (Verification and Validation) may not reveal all potential software errors, yet manufacturers may be unwilling to release source code. Hence it may be necessary to rely on 3rd party certification, which itself has a record of being less-than-perfect.

Software V&V is especially important for high-integrity devices. Figure 10 shows a typical flowchart for software development- the so-called 'V-model'.

Operating system software[8] can itself contain errors which may cause safety-related failures. Because of its size and complexity, Windows should not normally be regarded as suitable for safety-related applications.

Wireless sensors are a recent development with attractive properties such as low cost of installation and ease of commissioning. However these are not yet suitable for safety-related applications (and may never be so).

[8] *This is non-user specified software that manages:*

(i) PES hardware,

(ii) communication with external devices,

(iii) internal resources.

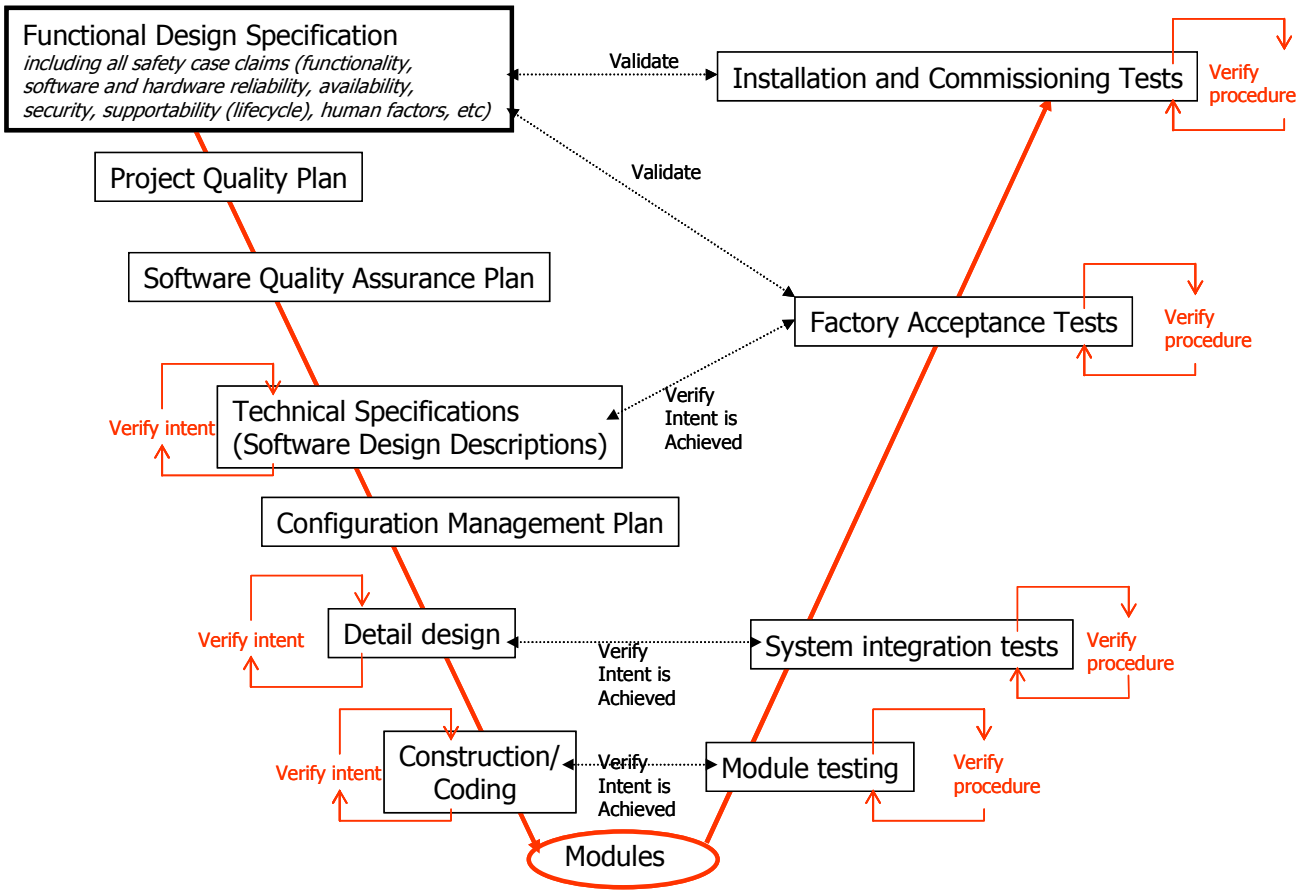


Figure 10: Typical V-model for Software Verification and Validation (V&V).

4.4.3.7 Maintenance management

Good maintenance management processes and practices are central to ensuring that ageing safety-related EC&I systems and equipment continue to operate reliably and with good availability.

Key aspects of maintenance management are as follows:

1. Maintenance Planning
    a. Is EC&I equipment classified according to its safety function?
    b. Are there performance standards
    c. Are there Maintenance, Inspection and Testing (MIT) plans in place?
    d. Is the MIT backlog monitored?
    e. Overrides

2. Procurement - Spares and Support Issues
    a. Spares availability and storage
    b. Contractual arrangements
    c. Change control
    d. Contingency planning and related QA issues

3. KPIs for Management of EC&I Ageing – lagging and leading indicators

4. Plant History
    a. Does the organisation keep failure data?
    b. Does it seek to learn from others' failure?

5. Specific Ageing and Failure Mechanisms

Maintenance Planning

Good maintenance planning is absolutely key to life management of safety-related EC&I equipment. Key issues are as follows:

- Safety-related EC&I equipment should have defined performance standards.
- Safety-related EC&I equipment should have Maintenance, Inspection and Test (MIT) plans in place, including calibration checks/ recalibration.
- Testing should be designed to confirm that safety-related functions are being performed properly.
- Test frequencies should preferably be risk-based.
- Non-safety-related EC&I systems, if they fail, may challenge safety-related equipment.
- Good practice is to have a maintenance policy document for EC&I equipment.
- There should be clear evidence of well-planned MIT arrangements and activities, including evidence (KPIs) that the maintenance backlog is being properly managed.
- There should be robust managerial controls over the assessment, approval, application and removal of all overrides.

Procurement – Spares and Support Issues

So-called EC&I 'ageing' or obsolescence in practice is most often determined by spares availability. OEM contracts may expire after a given number of years, and spares become unavailable. However, EC&I equipment can in some instances, and with care and forethought, be operated safely well beyond this point. The key issues comprise:

- Adequate spares holding, in good storage conditions, by the Operator.
- Long-term support contracts with the OEM.
- Specialist contractors for some component repair.

- Awareness of the risk of lack of change control over time in the supply of spares from the OEM – especially for digital components.
- QA issues around buying second-hand components, e.g. from eBay.

Plant History and Other Experience

Some form of accessible record of plant component failures is highly desirable. Such a record achieves, inter alia, the following:

- It enables the Maintenance Department to identify where re-working is needed and where repeat failures occur, thus enabling smarter solutions to plant problems.
- It improves Operator awareness of component unreliabilities.
- It enables Technical or Engineering Departments to identify those components which have a significant adverse contribution to plant availability and safety.
- If relevant, it enables more accurate Quantified Risk Assessments of the plant.

Ideally, an organisation may also have access to cross-industry sources of information which improve awareness, and enable learning from, incidents and accidents which have occurred elsewhere.

Also relevant here is history of the use of overrides.

KPIs for Management of EC&I Ageing

Extensive advice of the use and development of process safety KPIs is available elsewhere – see for example:

- HSE, *Developing Process Safety Indicators*, 2006
- Process safety KPI downloads available from www.aiche.org/ccps/metrics

Both leading and lagging indicators should be used as KPIs. Lagging indicators measure *outcome*, whereas leading indicators measure *processes or inputs that are needed to deliver the desired safety outcome.* In general, lagging indicators are easier to measure and more reliable, but they only show what has already happened, whereas good leading indicators should forewarn of future difficulties.

Ideas for Process KPIs related to EC&I ageing will be developed in the Phase 2 report.

Specific Ageing and Failure Mechanisms

For the Phase 2 report, high-level technical information will be presented regarding specific EC&I ageing and failure mechanisms. This will include:

- A summary of basic terminology relating to integrated circuit (IC) failure mechanisms.
- Basic information relating to cable types and their ageing mechanisms.

- Other information as appropriate. This is expected to include transformers, motors and generators, and switchgear.

4.4.3.8 Management of Change

Suitable arrangements and skills for Management of Change (MoC) are essential for managing ageing EC&I equipment.

Solutions to EC&I refurbishment projects or upgrades using purely analogue equipment are now extremely difficult, since new analogue equipment is becoming increasingly difficult to procure. Hence almost all new EC&I equipment is digital.

In the recent past, there has been a record of some EC&I projects (and in the wider sense, major IT projects in general) failing to achieve their objectives. Some of these failures have been due to the very complexity that software-based solutions make possible. Other failures have been due to the problems of safety justification of software-based systems.

Hence the replacement of ageing EC&I equipment requires that Operators have proper arrangements for MoC. This section describes good practice for MoC, comprising:

1. High-level issues about the Company MoC capability.
2. Software maintenance and configuration management.
3. Project management issues.
4. Competency management for EC&I maintenance, testing, modification, and refurbishment.

Each of these is discussed in turn below.

<u>Management of Change (MoC) capability</u>

In order to be able to upgrade ageing analogue equipment to modern digital equipment, the Operator needs to have robust MoC arrangements in place in accordance with IEC 61508 or IEC 61511.

The main issues for MoC are:

1. Do staff have the necessary skills?
2. Does the MoC process cover the essential aspects of IEC61508/IEC 61511? These include:
    a. Functional Safety Management
    b. SIL requirements assessment
    c. Equipment SIL rating
    d. Software maintenance arrangements
    e. Software configuration management

<u>Software maintenance and configuration management of plant computer systems</u>

Plant computer systems such as DCS can be very large and complex, sometimes with millions of lines of code (LoC). Maintenance of these systems, which will in general be safety-related, requires care, attention, effort and resources.

Further details, definitions and expectations for software maintenance and configuration management will be presented in the Phase 2 report. Key points include:

1. There is normally a need for software-focused MoC arrangements.
2. Software versions should be clearly identified. If the software history is uncertain, a 'baseline' configuration for the application software should be produced.
3. All safety-related functionality in the software should be clearly defined.
4. Software QA plans (SQAPs) should be produced defining QA responsibilities, procedures and standards.

A particular issue with older programmable DCS may be the use of obsolete computer languages. The availability of programmers for old languages can be difficult.

Many of these issues may also apply to smaller software-based systems, e.g. discrete plant monitoring systems, some of which may be safety-related.

Project management issues for large EC&I refurbishment projects

In the recent past, there has been a record of some EC&I projects (and in the wider sense, major IT projects in general) failing to achieve their objectives. Some of these failures have been due to the very complexity that software-based solutions make possible[9]. Other failures have been due to the problems of safety justification of software-based systems.

Sound project management arrangements can go a long way to help mitigate the risks of project failure – further details are provided in Appendix 4.

Competency management for EC&I maintenance, testing, modification, and refurbishment

Clear management systems should be in place for the full life-cycle of instrument-based protective systems, so that activities are planned, executed and documented to assure the required performance.

These management systems should include competence assessment, and the identification in writing of individuals with key responsibilities.

[9] *For example, the French N4 Chooz B nuclear power station suffered delays due to the cancellation of the P20 control and monitoring system. The primary technical difficulty faced by the P20 system was that the software for the system had become too complex to be verified effectively and confidently.*

4.4.4 Management Systems

4.4.4.1 Elements of Management Systems and the Impact on the Aged/Ageing Plant Issues

Key elements of a management system designed to be capable of recognising and managing plant ageing are illustrated on Figure 11.

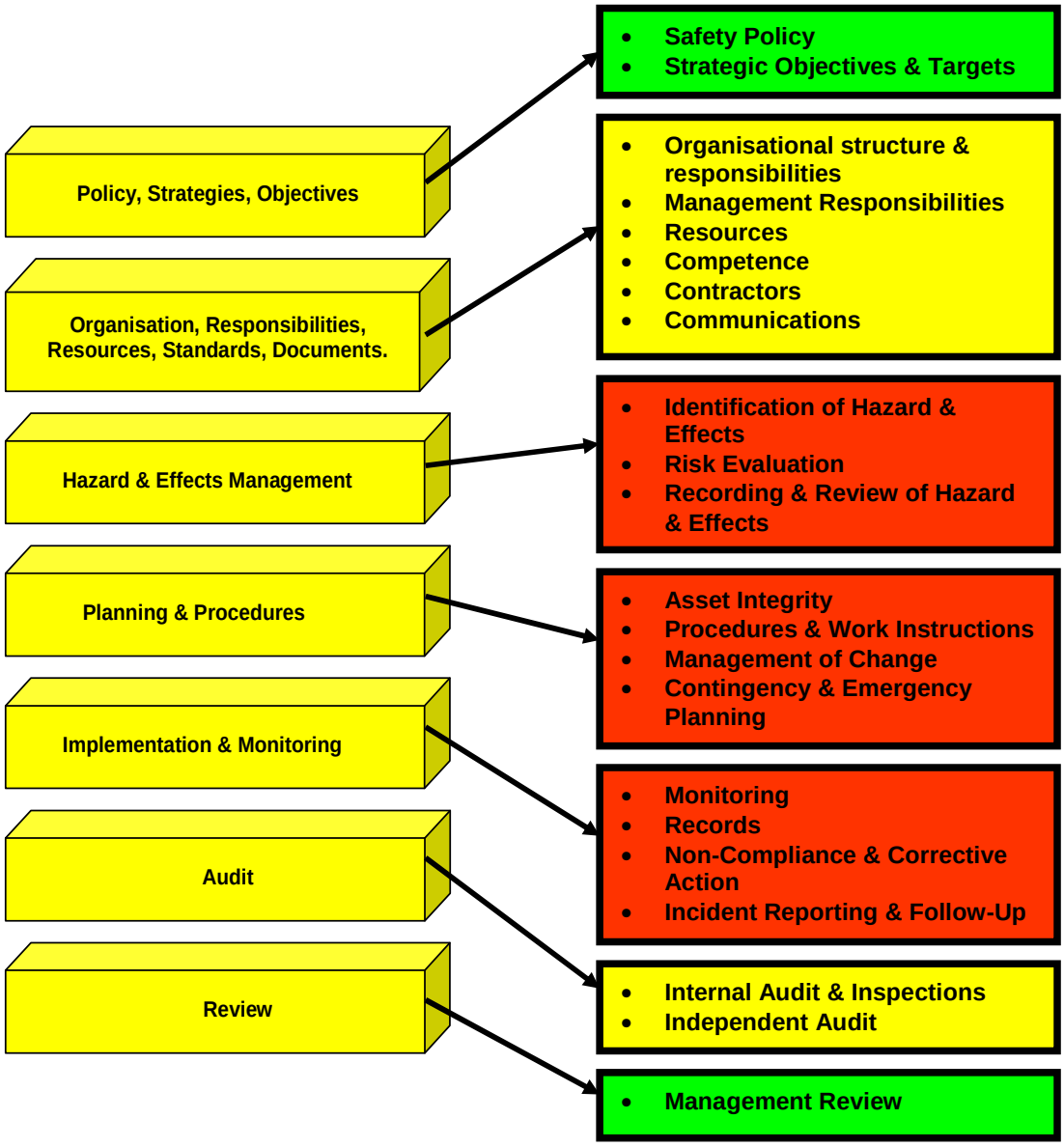


Figure 11: Elements of a Management System Capable of Managing Plant Ageing Issues.

The development and maintenance of a well defined **Safety Management System** is the key to ensuring that plant and equipment is purchased, constructed, maintained and reviewed in a structured way. This will reduce the potential for conditions to develop which could give rise to major incidents. Such a system will also ensure the effects of change, and the life cycle of

the operation is monitored, reducing the development and effects of ageing and the potential for an incident to be realised due to aged or ageing conditions.

Although it may be said that every element of a good management system can have an influence on this outcome, the following elements could be seen as the main sections that require the most focus.

- A well **organised** and structured company and its departments are vital to good safety management, setting out clear **responsibilities** and lines of **communication**. This will ensure that all levels of staff are aware of any change and are prepared to communicate their observations in relation to changes in operations and hardware.

- Managing **resources** to ensure **knowledge** retention, and the maintenance of a well structured **competency** development programmes to give the skills to manage and maintain plant and equipment, is essential.

- It is also important to include the management of contractors in this process, ensuring that they are aware of the requirements of the interface with the operation in relation to responsibilities, resources, competence and communication.

- **Standards** associated with plant and equipment must be maintained ensuring that any changes that are required over time are put into practice and documented. If the correct standards, and operational practices for plant, equipment and structures are not maintained this can have a significant effect on the life of the components involved.

- A well developed process for the identification of **hazard and their effects,** including a **risk evaluation** procedure, must be maintained. As plant operations and conditions develop and change over the years, the effects must be assessed and the responsibility for completing actions is identified, ensuring close-out is completed and recorded. It is important that the details of these assessments are reviewed at management team level on a regular basis to ensure senior managers are aware of any priority issues.

- The **planning** of improvements or upgrades to plant and equipment must be supported by risk evaluation and assessment in respect of the effect on existing plant and structures. **Procedures** which are produced to operate plant and equipment require review to account for possible changes over time. A review of these procedures must be identified in the management action plan and a clear time scale for such reviews must be identified in the documentation. **Documentation** must be maintained to reflect the current condition of the plant and to provide a record of its history as any changes are made.

- The development and **implementation** of procedures covering asset integrity management and management of change are key in **monitoring** plant and equipment throughout its operational life, along with well structured maintenance management systems. Deterioration of plant, equipment and structures whether due simply to its age or exposure to operational or environment conditions which may induce ageing, must be closely monitored and its continuous fitness for purpose assessed.

To ensure any management system is working correctly, and is being maintained, a series of both visual inspections and systems **audits** is essential. The audit plan must include specific aspects of the management system and operation, also internal and independent audits of

the full management system must be planned to ensure the system, and its components, are being maintained to the required standard laid down by the company.

Having identified the priority areas of a structured Safety Management Systems there are a number of reasons why these may fail, resulting in incidents.

- Poor overall safety culture where senior/middle management fail to recognise safety issues and fail to maintain avenues of communication such as safety briefings and tool box talks in order to raise potential problems.

- Failure to pre-plan for retirement of experienced staff leaving no time for the transfer of knowledge. The skills associated with the operation and performance of old plant and equipment is lost.

- Failure to maintain a structured competency management system where training is give but no competency testing or refresher training is carried out.

- Failure to recognise that contractors develop skills and knowledge of an operation and then failing to recognise the effect that changing contractors will have on the operation, particularly relating to older plant operations.

- The standards relating to operating and maintaining aged plant and equipment must be reviewed and updated as required but these are often overlooked.

- The failure to ensure that identification of Hazards & Effects and Risk Evaluation is done on a continuous basis and that it is not just a 'one off' exercise. Review of all Risk Assessment must be done when changes are made or within a defined period of time, which must be stated within the Management System. This is often not done.

- New upgrades/additions to existing plant and equipment are often done without additional assessment of the effects on the old plant or interface equipment.

- Although many businesses have asset integrity management systems and various maintenance management systems in place, often operational pressures encourage variations to these to be used. This quite often results in the missing of vital inspections and testing, and the putting off of replacement or renewal of equipment.

- Management of Change is increasingly implemented in business but quite often the process is seen as restrictive and it is not fully maintained with areas of the process allowed to lapse.

- Many of the requirements identified in the points above form part of the Management of Change process therefore failure to maintain any one of these will result in potential incidents especially when dealing with aged/ageing plant and equipment.

- Quite often audit plans are not produced in a structured way; also planned audits are cancelled due to other pressures in the business. Both visual and systems audit must be completed on schedule and form part of the KPI reviewed by the management team associated with any continuous improvement plan.

4.4.4.2 Data Review

Identifying Management Systems failings directly in relation to ageing plant issues is not always possible from the data supplied and also given the limited text in the data records.

However it must be considered that all aspects of management systems and procedures can affect the performance of plant and equipment throughout its life cycle, particularly in relation to maintenance management, competency development, training and hazard and effects management.

As plant ages either through its normal operational life cycle expectancy or increased exposure to external conditions and/or changes in operational conditions effecting its performance, management systems need to be updated and reviewed to ensure all the potential failings are identified and controlled. These types of detail have tended not to form a part of the incident reports reviewed in this project.

The review of data relating to incidents has highlighted relatively few incidents that can be attributed directly to management system issues. The number of incidents that have text that indicates some form of management weakness or omission or in fact human factors failings is in the region of 84 from a total number of incidents in the region of six thousand from the MHIDAS, RIDDOR and MARS databases but, as has been stated, few if any of these can be directly related to ageing plant.

Procedures were highlighted as being an influence in 43% of the Management Systems incidents. For ageing plant this could develop from failure to update operational process procedures as plant and equipment life is extended or failure to update procedures that may protect plant from the effects of ageing such as improving maintenance regimes, inspection and audit schedules.

Standards were identified in 24% of the incidents that indicated some level of management system failure; this included the availability of a competent workforce. The issue that arises here with ageing plant is the failure to maintain operational knowledge of plant and equipment due to turnover of staff. The lack of good training and development programmes linked with competency testing will contribute to reduced knowledge in the workforce operating ageing plan, and equipment. This applies to both own staff and contractors.

Hazard and Effects Management weaknesses were recognised in 18% of the incidents identified but yet again none of these could be directly identified with ageing plant. The relevance of H&E management to the ageing plant issue is where there is a lack of any risk review process in place to identify changed hazard scenarios throughout the plant and equipment life. The issue is particularly relevant to ageing which could be due to environmental or changed operational exposure affecting the plant, and not necessarily to the ultimate age of the plant.

Management Systems are a means of ensuring all aspects of HSE management are considered throughout a businesses operation and life cycle. The following areas are key to controlling ageing and aged plant and equipment.

- Management of Change process across all areas including procedures, equipment and staff, including contractors.
- Competence development and training programmes
- Review of updated standards against existing plant and equipment operation.
- Maintenance of a structured Risk Assessment process.
- Regular procedural reviews and updates by competent staff, against operational changes.

Although the data reviewed does not provide significant statistical evidence for management systems ageing, it cannot be concluded that it is not a problem that requires identification and suitable action.

To illustrate the issues arising from the review a number of specific incidents are highlighted below.

The following major incidents happened in UK refinery process plants and from the limited detail of the incidents it can be said that an element of ageing plant and systems had a significant influence in their development. In one report it indicates that the plant was circa 1950's vintage and in the second the plant had been commissioned in the early 1970's and the modifications done shortly afterwards.

In the first incident it was a case of the branch pipe being left and effectively forgotten about with no proactive monitoring/management of sections of the pipework so that over the year's corrosion and then the effects of stresses, from the process operations, caused the weld to fracture.

In the second incident the modification was made with no consideration of the effect over time, and the consequences of change in operation that the injection system would have on the pipework.

Lessons Learnt	**Comprehensive MoC procedures are required**
Data Source	**MARS**
Case ID	**# GB/2000/004-[02]**
Primary Cause of Incident	**Poor change control leading to fatigue failure**
Description of Incident	**A branch line failed at a welded joint to the main transfer line.** **The branch had inadequate support and was vulnerable to vibration fatigue and/or shock loading; it was old plant, circa 1950's vintage. The cause of the leak was subsequently found to be the fracture of a redundant, unsupported 6 x 3" reducing tee branch pipe to the main transfer line due to fatigue failure.** **A change was made to the configuration of the branch pre-1987 but there was poor change control. The pipework was inspected for corrosion only and there were no proactive surveys for dead legs/redundant drains. Loss of containment of approximately 11.5 tonnes of flammable hydrocarbons at elevated temperature, following the failure of a 3" branch on transfer line between fractionation columns, on fluidised catalytic cracker unit recovery section. The release ignited and the subsequent fire caused extensive damage to the plant. No serious injuries.** **Between spring 1998 and June 2000 there was an increased number of start ups and shut downs on the Vapour Recovery Unit further to this, a number of incidents had occurred during the two years prior to this incident in which vibration was a relevant issue.**

Lessons Learnt	Comprehensive MoC procedures are required
Data Source	MARS
Case ID	# GB/2000/004-[02]
	There were serious operational problems associated with the FCCU stage two modifications in 1997/98 which were a relevant underlying cause of this major accident. These were inadequately dealt with by the company despite recommendations in writing from the HSE to review the process after a previous incident.
Risk Control System	MoC Procedures

Lessons Learnt	Comprehensive MoC procedures are required
Data Source	MARS
Case ID	# GB/2001/010-[02]
Primary Cause of Incident	Poor change control leading to erosion/corrosion failure
Description of Incident	A catastrophic failure occurred on a section of pipework on the Saturate Gas Plant (SGP), at an elbow just downstream of a water-into-gas injection point. The 6 inch diameter pipe (the overhead line carrying flammable gas under high pressure) ruptured releasing a huge cloud containing around 90% ethane/propane/butane. About 20-30 seconds later the gas cloud ignited, resulting in a massive explosion and fire The primary cause of the explosion was the erosion/corrosion of the 6 inch diameter pipe which carried the overhead line from the De-ethaniser to the Heat Exchanger in the Saturate Gas Plant (SGP). The failure occurred downstream of, and in close proximity to, a water injection point that was not part of the original design. The design and installation of the water injection point in the pipe was not subject to any management of change assessment. No assessment was made of the changes in the use of the water injection point, between continuous and intermittent, over the lifetime of the plant. The frequency of use was a major factor in the rate of the corrosion of the pipework. During periods of continued use more frequent or detailed inspections of the pipework should have taken place to adequately monitor the integrity of the pipe. Corrosion management on the SGP was not sufficiently thorough or systematic to prevent the failure of the pipe. Some positive actions were taken, including the appointment of a full-time corrosion engineer for the refinery, the introduction of divisional corrosion reviews and monitoring of process streams by sampling, and the installation of corrosion probes, following receipt of specific

Lessons Learnt	Comprehensive MoC procedures are required
Data Source	MARS
Case ID	# GB/2001/010-[02]
	information in 1992 about the vulnerability of carbon steel pipework in the vicinity of water injection points. Unfortunately these activities were allowed to lapse with the result that there was both insufficient data on, and inadequate resource or focus applied to, corrosion as a potential major accident initiator on the SGP.
Risk Control System	MoC Procedures

In both incidents it is obvious that good, well maintained, HSE Management System procedures would have significantly reduced the potential for these incidents to have been realised.

The following issues relating to Management Systems can be identified:

1. Management of change procedures were not implemented.

2. In both cases the weakness of audit and the subsequent action tracking process contributed to the potential failures not being recognised and controlled. Prior to the first incident cited recommendations to review the process had been given by the HSE.

3. Poor initial design contributed to the eventual failure after many years in service.

4. A clearly developed Hazard and Effects Management process with a structured review procedure should have identified the potential for failure in both incidents.

5. Maintenance and Corrosion managements systems/procedures/technical reviews, were not focused enough to identify potential failures.

6. Staff competence and management commitment must be questioned in the second incident cited as it was indicated that the corrosion management system was allowed to lapse.

In both these incidents the condition which eventually resulted in a major release developed over a significant period of time. These conditions could have been identified and action taken to prevent them had there been a more focused HSE management culture linked to well maintained management systems.

Although the detail of the following incident is limited it can be identified that the equipment is old and that the operation had not been updated for a number of years contributing significantly to the eventual outcome of runaway and uncontrolled release.

Lessons Learnt	Need for comprehensive training and adequate procedures
Data Source	**MARS**
Case ID	**-**
Primary Cause of Incident	**Insufficient training, lack of procedures**
Description of Incident	**An unexpected rise in pressure in a batch reactor generated a runaway reaction. An operator error due to insufficient training, lack of procedures and the poor access to valves which meant that the vent line remained closed, resulted in a runaway reaction when the components were mixed, pressuring up the reactor. The reactor was more than 30 years old and there were no design standards available. Modifications had been made in order to clean the reactor more easily but there were no containment systems to prevent release of toxic material to the environment, a rupture disc in the system was set at 3bar. The operation was carried out manually and there were no other interlock protections in the system to control a runaway situation.**
Risk Control System	**Training**

The incident above captures a number of issues relating to ageing/aged plant as follows:

1. There were no standards / procedures available for the reactor which was more than thirty years old. There seemed to be very little evidence of maintenance management procedures.

2. Modifications had been carried out but this was only to aid the cleaning of the reactor.

3. There appears to have been no on going risk management or improvement programme for the operation of the reactor.

4. The operator had only six months experience of the process indicating that his competence may not have been tested, although he did ask for help from a colleague.

5. It could be possible that the older operators with experience and knowledge had moved on without it being confirmed that their knowledge had been passed on.

Key issues/questions related to Management Systems of Ageing Plant are summarised below:

1. Do management systems recognise the existence of aged plant and ensuring suitable attention is paid to this (identification and awareness of the issue) ?

2. Are mechanisms in place to identify new codes, standards, lessons learnt, or good practice and to review these to check the implications for existing plant ?

3. Do Management of Change arrangements exist to identify and assess changes to plant, structures, processes or operating / maintenance regimes which could invalidate the original design or lead to accelerated ageing ?

4. Are there system to gather information from inspections, surveys, audits, maintenance systems, incidents reports, etc and analyse these to help identify any trends or issues AND feedback mechanisms to update these arrangements (e.g. change inspection frequency) if an issue is identified or suspected ?

5. Do these inspections etc extend to civil and structural features of the plant and safeguards eg flood control embankment, ground subsidence, integrity of paved areas, drainage systems and bunds, buildings, walls, plant supports, pipebridges, pits and culverts, tall structures, etc ?

6. Are there Management of Change / Competency Assurance arrangements to ensure key skills, knowledge and experience with aged plant is retained, especially as older personnel retire or move on or when reducing manning levels or when outsourcing maintenance work for example. Are there suitable qualified resources available to identify and address ageing issues, i.e. competent corrosions engineers, structural/ mechanical engineers, EC&I specialists, etc?

4.4.5 Structures

The data review has highlighted a small number of incidents related to the ageing of structures. These are not statistically significant but, as for management systems, it is considered that the nature of the databases does not lend itself directly to reporting of such incidents, i.e. most are concerned with loss of primary containment and do not focus on the types of asset represented by this category.

However, a number of incidents illustrating the main issues are summarised below.

MHIDAS

- An incident occurred where a wall collapsed onto some pipework causing an acid line to rupture. #2616
- Structural failure of a mixer bearing support led to frictional heat causing a runaway reaction in a reactor. #3096
- 1te molten resin spilled from a tank. The spill occurred when the vessel tipped over after a heating jacket at its base fell off. #9820

MARS

- An explosion with subsequent fire occurred in the cellars of the administrative building of the company. Investigation suggests that nearby underground pipework may have been leaking which allowed flammable material to enter the cellar area via various hollow pipes, unsealed cable access routes, and vaults, etc under the building. #DE/1995/004-[01]
- Two barges, one carrying benzene, were heading up the Rhône towards Lyons pushed by a tug. A safety hawser parted, the barges "jack-knifed" and the tug was sunk. #FR/2004/003-[02]
- Release of 8,000 tonnes of highly flammable liquid via floating roof drain of 11,000 m^3 gasoline tank. All spill contained within bund and recovered. Leak was via an internal floating roof drain line which was of poor welded quality. #GB/1998/002-[01]

- A 3" carbon steel branch (redundant) to a transfer line between a debutaniser column and re-run column on recovery section of cracker, causing a loss of containment of approximately 11.5 tonnes of flammable hydrocarbons at elevated temperature. Branch failed at welded joint to main transfer line. The branch had inadequate support and was vulnerable to vibration fatigue. #GB/2000/002-[02]
- A dam failure at the tailings-pond outside a mine caused more than 2 million m^3 of water to be released from the tailings-pond. The treated water, with less than 4 mg/l dissolved copper content was released into a tributary of a River. #SE/2000/002-[01]
- A sulphuric acid cistern collapsed, which at the time contained 16,300 tons of 96 % sulphuric acid, releasing its contents into the adjacent Harbour. The cause of this incident has been assessed to be a leak in a coolant supply pipe, which caused a weakening of the ground under the tank farm. This led to instability in the cistern, which subsequently split. The dyking was also damaged. #SE/2005/001-[01]
- A pressurized natural gas leaked from a pipeline that transfers gas to underground caverns. The leaked gas found its way through old abandoned wells to sites above ground and formed eight geysers of natural gas. Two explosions and fires resulted that killed one person and critically wounded another. The gas leak and fire lasted several days. # US/2001/005-[01]

RIDDOR

- Loss of some 19 tonnes of concentrated sulphuric acid from a high level cast iron pipeline. The company have a long-standing scaffolding system to provide access to the pipelines at high level on the pipe-bridge. Subsequent investigations revealed that part of the scaffolding was resting on the top of the pipeline at the neck of the screwed flange connection. This had allowed local corrosion to occur undetected between the scaffolding and the cast iron pipework causing the wall thickness to reduce to 1.5 mm (4mm original). #1885522
- Following extensive flooding a 400mm section of a 24" diameter 7 bar steel pipeline had become exposed adjacent to a river. Immediate action was taken to evaluate the effect on the integrity of the pipeline. Survey revealed no risk to the integrity of the pipeline. River bank reinstated. This may not be an age related issue as it is not clear if there was any failure of the river bank or other flood defence provisions. #4071663
- There was an escape of dirty water and slurry from a coal mine slurry storage area, due to a sudden breach in the embankment separating the storage area from an adjacent water collection pond. Incident investigation stressed the need for clear policy and instructions to control the construction, modification, use and maintenance of structures which are intended for, or might be used for, retaining substances which might flow when wet. #4072417

There were also a number of bund failures, these are summarised in the Safeguards Analysis.

The key question for structures appears to be that from the review of Management Systems, i.e. whether or not inspections extend to civil and structural features of the plant and safeguards eg flood control embankment, ground subsidence, integrity of paved areas, drainage systems and bunds, buildings, walls, plant supports, pipebridges, pits and culverts,

tall structures, etc. If so, how are the data handled and are these assets part of the integrity management system for the plant in terms of periodic review.

4.4.6 Safeguards

Introduction

An analysis of incident and dangerous occurrence data has been undertaken to identify those events where the reliability or effectiveness of safeguard systems could have been compromised by ageing factors. Safeguards have been taken as any technical (hardware) control or mitigation equipment or systems relevant to the incident. EC&I equipment has been excluded, as these are considered separately.

Results

In the examples extracted below, the database identifiers or RIDDOR case numbers (#numbers) are also provided.

MHIDAS Examples

The MHIDAS database only contains limited text descriptive information on the incidents, and few records commented on the role of any safeguards. The issues highlighted below should be treated as useful anecdotes rather than an indication of the extent of, or any trends in, safeguards ageing.

- Detectors failed to operate. #1907
- Unable to shut down plant. #3451
- Several warning sirens inoperable. #10054
- Fire-Water pumps malfunctioned. #9490
- Leaking solvent seeped into the soil via a cracked drain. #12729
- Water sprays ineffective in dispersing vapours (may not be age related, no details given). #510
- A monitoring system which would have alerted staff had broken down and a vent which would have released pressure had been bolted down #10159
- The sprinkler and deluge systems were overwhelmed by the fire and one of two fire pumps failed. #2551
- Sump-pump and alarm failures. #10850
- (Unspecified) safety system failures but events suggest these included pressure relief systems. #1187, #6440

There were several examples of bunds working well, and other of bunds being overtopped and one case of bund wall collapse after an exploding tank fell on it – but these are not considered to be ageing issues.

(2951 events in MHIDAS data extract reviewed, those listed represent 11 / 2951, approximately 0.4%)

MARS Database

The MARS data contains more textual descriptions than MHIDAS, but these are subject to similar limitations in terms of the role and effectiveness of safeguards. The same comments apply.

- Cooling water failure to reactor. #DE/1983/003-[01]
- Rupture of a membrane of a pressure regulator. #DE/1984/003-[01]
- Failure of remote isolation system for pipeline. #DE/1988/001-[01]
- Unable to close two manual isolation valves to isolate a leak (valves would not close). #DE/1991/004-[01]
- Failure of safety (pressure relief) valve. #ES/1993/002-[01]
- 'Refrigeration' (i.e. cooling/ deluge) systems of the tanks (were initiated), some of which failed. #ES/1996/003-[01]
- Emergency back-up diesel generator took too long to start-up following a power supply failure at a plant, leading to temporary loss of cooling of reactor. #FR/2005/001-[01]
- A toluene detector in the effluent line failed to activate a system which would have diverted the effluent stream to a dump tank. As a result the toluene entered a public sewer (Note: this may be an EC&I example). #GB/1986/002-[01]
- A poppet valve failed to operate due to bearing friction problem, causing it to jam in an intermediate position, leading to level problem and leak in a Gas Holder. #GB/1987/002-[01]
- Jammed manual isolations valves, passing isolation valves and blocked drain lines in flare system due to build up of sludge over time (several examples in data of blocked lines etc due to debris, sludge etc – this may be considered an ageing issue in terms of plant maintenance / management but are not an ageing equipment issue). #GB/1987/004-[01]
- Operation of the ESD valve from the control room failed in a pipeline leak and it had to be closed locally (Note: this may be an EC&I related example). #GB/1994/002-[01]
- Upstream 'Anti-vacuum' device installed to prevent siphoning failed. #GB/1997/001-[01]
- Isolation valves to adjacent coolant surge drum failed to operate on demand (Note: this may be an EC&I related example). #GB/1999/006-[01]
- Attempts were made to close the (isolation) valve from the local control panel but this was unsuccessful. #GB/2002/001-[02]
- Following a tank leak, the bund/ safety basin also leaked due to a number of cracks in the walls that allowed some of the released amount to spread further into the ground and to the sea. #NO/2001/001-[01]

(348 events in MARS data extract reviewed, those listed represent 15 / 348, approximately 4%)

RIDDOR Database

The RIDDOR data provided by HSE was filtered to identify those events which involved a loss of containment event, as the primary focus of this study is on events with a major hazard potential and involving the release of dangerous substances.

As with the MHIDAS database, the RIDDOR database entries only contain limited text descriptive information on the incidents, and few records commented on the role of any

safeguards. The issues highlighted below should be treated as useful anecdotes rather than an indication of the extent of, or any trends in, safeguards ageing.

- Export pipeline ESDV passing when tested. #1021047
- Passing bund drain valve. #1880490
- Pressure relief valve failed to operate. #1880499
- Faulty vent valve due to actuator solenoid problem causing spurious venting of process. #1880680
- Bund in poor state of repair. #1880742
- Tank isolation valve found to be passing. #1880778
- Chemically resistant cement lined bund found to be seeping, where bund wall met floor, after tank spill. #1880823
- Earth bonding on reactor process system in poor condition, potential for electrostatic build up providing an ignition source. #1882431
- NRV's used to isolate surge drum failed to close on operation of Warwick mechanical actuation mechanism. #1883590
- Released acid was initially contained within a concrete bund but the acid eventually found its way out of the bund via some failed sealing compound between adjacent concrete slabs making up the bund floor. #1884517
- Oil circuit should have been drained down in an incident but the drain line was blocked. Also concern on poor condition of emergency telephones. #1885075
- Pipeline Riser ESD Valve failed to close completely on demand during a planned routine full closure test. Lubrication and valve stroking cleared the problem. #4099851
- During routine testing of a 3 inch of methanol riser valve the valve failed to close remaining 25% open. The valve required lubrication in order to regain full closure functionally. Suggested that corrosion, or a combination of wear and corrosion, were responsible for the failure to close of the 12 year old valve. #4103856

(3142 events in the filtered data extract, and 527 of these further extracted using a keyword search for safeguards related systems. The possibly age related failure events identified represent 13 / 3142, approximately 0.4% of all events).

Possible Process ‘Ageing’ Issues?

Several examples can be found in the data of the build up of flammable, pyrophoric, reactive or otherwise hazardous deposits, dusts or sludge in the process, drains and vent systems over many years, that can present fouling, a blockage / flow restriction hazard or a fire/ thermal decomposition hazard if they dry out, are contacted by acid/alkali wash materials for example, or are exposed or disturbed during maintenance or cleaning for example. These incidents could be viewed as examples of process related ageing, increasing the risk of a major accident since the design ‘process conditions’ are not being maintained. Where such hazards are recognised, this may have taken into account in the design of the plant or in the specification of the inspection, maintenance and cleaning arrangements.

General Observations from the Data Searches with Respect to Safeguards

The most common (non EC&I) safeguards mentioned in the various incident data were plant isolation and shutdown systems, including remote operated shutdown/isolation valves, pressure relief/safety valves (and associated vents or flares), bursting discs, and active fire water systems including water sprays, monitors and water curtains, bunds or kerbing to contain spills and site alarms and sirens for warning nearby offsite populations.

The main EC&I safeguards mentioned were detectors and alarms for process level, pressure and composition, or for leak/ gas detection, and associated trip functions to shutdown plant, stop pumps/ transfers or isolate process feeds.

The data tended to mention only those specific safeguards that were used to combat the incident. As such it was not possible to identify all the relevant safeguards that were provided and the extent to which these worked or were successful. Only a few descriptions mentioned safeguard systems that had either failed or proved ineffective.

General Conclusions

An analysis of incident and dangerous occurrence data has been undertaken to identify those events where the reliability or effectiveness of safeguard systems could have been compromised by ageing factors. Safeguards have been taken as any technical (hardware) control or mitigation equipment or systems relevant to the incident. EC&I equipment has been excluded, as these are considered separately.

Few descriptors in the databases give any details on what safeguards were meant to be present and which, if any, failed and why. As such the data cannot be relied on to provide a robust indication of the extent to which ineffective safeguards may contribute to major accidents, nor can it indicate the extent to which ageing may have contributed to the safeguard failures or shortcomings.

However, the data does provide a number of examples highlighted in the results above that suggest specific safeguard failings that may be age related. It is not clear how many of these are entirely age related, but they do indicate a lack of appropriate testing, inspection or maintenance, or violations of safety arrangements over long periods of time.

It should also be noted that the data contains many references to safeguard systems that were:

- Insufficiently designed, manufactured, or sized
- Set to an unsuitable set point
- Defeated or disconnected
- Ignored or cancelled (e.g. Alarms)
- Available to help manage the incident but were not activated or used by the operators

Whilst these are important observations, these incidents have not been included in this analysis unless some ageing mechanism was also considered to be affecting the safeguard system's performance.

The data also records many situations where basic 'good practice' or 'industry standard' safeguards were not provided, such as high level alarms on tanks, suitable isolation valves (manual or remote operable), basic reactor interlocks, etc.

The types of ageing related failures recorded include:

- Inoperable, blocked, jammed or passing isolation valves, including ESD/ ROSOV valves
- Leaking bunds
- Cracked/ leaking drains
- Poor condition earth bonding
- Faulty vent and pressure/ vacuum relief valves

- Cooling water system failures
- Ineffective sprinkler and water deluge/ spray systems
- Emergency generator that failed to start / delayed start on demand leading to power loss
- Failure/ malfunction of fire water pumps to start on demand
- Inoperable site sirens /alarm
- Failure of monitoring / detection systems (these may be EC&I related)
- Failure of sump pumps to work on demand

An analysis of these safeguard ageing failure events is presented below. However, the breakdown by failure type should be treated with caution: the small number of events and shortcomings in the reporting systems means there is insufficient data to draw any conclusions on which systems are most prone to failures. For example, the high incidence of failure of isolation may be a reflection that the data being analysed is for loss of containment events, where isolation would be a key issue in the mind of the incident investigation team.

Table 9: Analysis of Ageing Safeguard Failure Events.

Safeguards Failure Type	No.	%age
Bund Leakage	4	10%
Cooling Water Failure	2	5%
Detection Failure	3	8%
Drain Failure (Cracked)	1	3%
Earthing Bond Deterioration	1	3%
Emergency Generator Failure to Start	1	3%
Fire Pump Failure to start	1	3%
Firewater Spray Inadequate	2	5%
Isolation Failure	14	36%
Level Failure (Gas Holder)	1	3%
Pressure / Vacuum Relief Failure	8	21%
Site Siren Failure	1	3%
Total	39	100%

The data also included several cases of scrubbers, interceptors, catch pots and other emission abatement or vent capture systems suffering containment failures or pump/ recirculation failures. These have been considered as primary containment and rotating equipment failures in this analysis, but could also be interpreted as failures of key safeguard systems for the protection of the environment.

The extent of age related shortcomings in safeguards systems is difficult to assess from the limited data available. The number of potential safeguard ‘ageing’ related problems from the analyses of the MHIDAS and RIDDOR data are comparable; both data indicates that these represent approximately 0.4% of all events. This is low, and probably is a reflection of the reporting which tends to focus on the primary causes of the leak or incident rather than any secondary or contributory failures. The MARS data contains more comprehensive event descriptions, and this is reflected in the increased probability of age related safeguards issues in the data, of the order of 4% of all events. It is considered that the true figure could be significantly higher than this, as a high degree of under-reporting is likely in terms of the role of safeguard systems in these incidents.

Some representative examples of the three most common failure types recorded are presented below (Isolation Failure, Pressure Relief and Bund Failure, respectively).

Isolation Failure

Lessons Learnt	**All safeguard systems need to be identified and appropriate inspection, maintenance and/or testing must be carried out to ensure that they can achieve their function.**
Data Source	**MARS Database (EU Seveso II Directive Reportable Incidents)**
Incident ID	**GB/1999/006-[01]**
Primary Cause of Incident	**(Possible) Ageing of safeguard system.**
Description of Incident	**Isododecane used as heat transfer medium during production of ethylene oxide. Drain piece on suction end of circulation pump failed due to vibration fatigue and released isododecane at 190ºC and 20 PSI. Ignited almost immediately. Pool fire affected plant and equipment in immediate vicinity.** **Plant shutdown and major emergency plan activated. Isolation valves to adjacent coolant surge drum failed to operate on demand which significantly prolonged the incident.** **Emergency services attended and contained the incident. Fire extinguished shortly after isolation valves successfully operated.** **Fire water run-off contained in bund. Subsequently transferred to road tanker for disposal as contaminated waste.**
Risk Control System	**Regular inspection, maintenance and testing of remote operated isolation valves by Competent Person**

Note: this is one of several incidents where panel operated valves failed to close on demand. It is not clear from the reports whether these failures were due to problems with the EC&I elements or the valve or actuator, but they nevertheless highlight the failure to isolate if systems are not regularly inspected and tested.

Lessons Learnt	**All safeguard systems need to be identified and appropriate inspection, maintenance and/or testing must be carried out to ensure that they can achieve their function.**
Data Source	**RIDDOR Database**
HSE Case ID	**4103856**
Primary Cause of Incident	**(Possible) Ageing of safeguard system.**
Description of Incident	**During routine testing of an offshore platform 3 inch methanol riser valve, the valve failed to close remaining 25% open. The valve required lubrication in order to regain full closure functionally.** **The most pertinent facts appear to be:** **The valve has been in place for over twelve years.** **Freeing the valve was associated with its lubrication; the valve is directly exposed to the elements through the grating below.** **This suggests that corrosion, or a combination of wear and corrosion, were responsible for the failure to close.** **Examination of the individual components of the valve system suggests that the actuator 'yoke' control mechanism is the most likely location for the seizure to have taken place. The fact that the valve operated normally up to three weeks before it failed suggests that failure cannot be predicted by condition monitoring.**
Risk Control System	**Increase testing frequency of valve to monthly both to test the valve and ensure it is operated frequently to stop its mechanism sticking. Increase maintenance frequency to include quarterly lubrication of valve and actuator mechanism.**

Pressure Relief Failure

Lessons Learnt	**All safeguard systems need to be identified and appropriate inspection, maintenance and/or testing must be carried out to ensure that they can achieve their function.**
Data Source	**RIDDOR Loss of Containment Data**
HSE Case ID	**1880499**
Primary Cause of Incident	**Ageing of safeguard system.**
Description of Incident	**Bursting disc on a plant failed leading to a release of a hot chemical mixture and subsequent fire which was quickly extinguished by deluge and on-site fire team. No injuries. Cause thought to be because associated vessels and pipework were overfilled with product and reactants which caused over pressure of vessels when starting plant up. A pump removing liquid from the bottoms pot failed temporarily, a Pressure Relief Valve (PRV) which would have relieved some pressure in the system on one vessel did not work, either the feed pipe to it was blocked or the PRV was defective. Maintenance of PRV is suspect, no records to show it had ever been maintained since first used in the 60's.**
Risk Control System	**Regular inspection, maintenance and testing of PRV by Competent Person** **Overfill protection may also be relevant.**

Bund Failure

Lessons Learnt	**All safeguard systems need to be identified and appropriate inspection, maintenance and/or testing must be carried out to ensure that they can achieve their function.**
Data Source	**RIDDOR Loss of Containment Data**
HSE Case ID	**1884517**
Primary Cause of Incident	**Ageing of safeguard system.**
Description of Incident	**Release of hydrogen chloride (HCl) from an above ground storage vessel. Approximately 20 tonnes of 32% HCl was released from a failed flange connection (corroded) at the base of a 90 tonne vertical storage vessel. The failure of the flange had occurred on the vessel side of an isolation valve. Consequently, the release could not be isolated due to acid, mist etc near the isolation valve. The released acid was initially contained within a concrete bund but the acid eventually found its way out of the bund via some failed sealing compound between adjacent concrete slabs making up the bund floor. The release was promptly dealt with by the company: A significant volume of acid was transferred from the leaking vessel to a road tanker, and water curtains were deployed to minimise the impact of the acid cloud that had formed.**
Risk Control System	**Regular inspection of bund by Competent Person Consider providing Remote Operated Shut Off Valve (ROSOV) on tank so can isolate these in an emergency.**

<u>Key questions for inspectors?</u>

General questions on safeguards:

1. Are there hazard or risk assessments in place and do these identify **all** the safeguards required?
2. Are safeguards provided to meet these requirements?
3. Are the safeguards adequate in terms of their capacity, speed of response, coverage etc to achieve the required functionality?
4. Are the safeguards adequate in terms of their availability, reliability, survivability and endurance to provide a high probability of working when required?
5. Are the safeguards recognised as HSE critical systems and included in the maintenance, testing and inspection arrangements?

Points 1-4 relate primarily to the design, specification and provision of safeguards, and are not ageing related.

In terms of ageing aspects, point 5 is the most relevant.

On a practical note, some hazard or risk assessments may take a somewhat focussed view on a task or operation to identify the key safeguards required, see point 1 above. For example these may identify process safeguards such as instrumentation, alarms, trips,

pressure relief etc, but might not look as far as plant and site drainage systems, area leak detection, bunding, general area alarms, overall fire fighting capability, escape routes, etc.

Inspectors should check that these more general safeguard systems and features are recognised as HSE critical and included in the maintenance, testing and inspection arrangements. The list of safety related systems (in Table 1) could be used as a prompt list to assist in these checks.

4.5 Review of HCR Offshore Data

This review examined the Offshore (OIR12) Hydrocarbon Leak Database. This is a detailed and comprehensive database of loss of containment incidents on Offshore Installations in the United Kingdom Continental Shelf. The database has been operating for over 15 years and reflects experience across a range of installations, many of which are old. The nature of the event data and population means that events can be analysed by failure cause for year on year populations, and average frequencies calculated by equipment year.

Although the offshore environment is different in some respects to onshore plant, in many cases similar processes are used and similar integrity management regimes are in place. The offshore industry has also been aware of the issue of ageing assets and various initiatives have been adopted to review and ensure the ongoing integrity of the processes and structures offshore. In this respect, the offshore data could be considered to represent a situation where ageing has been recognised and is being more actively managed that for many older onshore facilities.

The latest data downloaded from the HSE Hydrocarbon Release Systems website (https://www.hse.gov.uk/hcr3/) has been analysed, covering the period October 1992 to March 2008.

The data has been interrogated to identify the ages of the installations involved in the various loss of containment events. The results are presented below:

Table 10: Hydrocarbon Release Events by Age of Installation.

Installation Age Band (Years)	0-5	5-10	10-15	15-20	20+	Total
No. Releases	690	644	657	555	1098	3644
% of All Releases	18.9%	17.7%	18.0%	15.2%	30.1%	100.0%

This shows that a significant proportion of the leak events in the database were from installations which are over 20 years old: older than, or approaching there design life.

To assess if ageing may be an issue, the data has been cut into three periods, each of approximately 5 years duration and compared. Any increase in the frequency of events over these periods may be an indication of a deteriorating situation, which may be age related. The results are presented below. Two analyses are presented. The first only includes releases categorised as ‘Significant’ or ‘Major’ in severity – those likely to be considered of major hazard nature. The second analysis also includes those events classified as ‘Minor’, i.e. all reported events.

The results show that in general, the incidence of Major and Significant releases is falling with time (Table 11). This indicates that despite the aged nature of some of the facilities, the

inspection and maintenance regimes in place appear to be working, and are securing reductions in the frequency of leaks that might present major hazard potential. It should also be noted that some older facilities are experiencing lower operating pressure and flows than originally designed for due to declining reservoir conditions. This may to an extent offset some deterioration due to ageing.

An analysis of all leaks (Table 12) shows that whilst the annual average numbers of leaks over time may be declining, the actual overall trend is slightly upwards when the data is normalised by taking into account the equipment populations. This increase may be partly explained by an increased reporting of minor leaks, rather than an actual increase in the number of leaks occurring. Further investigation of the frequency of leak events by cause shows that for most causes, the frequency of leaks is steady or falling. However, the data suggests that there may be an increase in the frequency of leaks caused by corrosion and mechanical fatigue and wear. The relevant data is highlighted in Table 12. Care must be taken in drawing hard conclusions from the data due to the relative simplicity of the cause classification and reporting system, but the data may indicate that ageing may be increasing the probability of small leaks/ failures due to these mechanisms. It is also possible to speculate from the data that the frequency of leaks due to internal corrosion and mechanical fatigue/ wear may be 'flattening off' over recent years as the issue of ageing has been brought into focus.

Overall, it should be noted that these 'age related' causes only account for approximately 20% of all leak events. Operational causes, design faults and mechanical failures are the main leak contributors.

Table 11: Hydrocarbon Release Events Analysis – Major Hazard Potential 'Significant and Major' Severity Events.

Causation Category		Average Events per Annum in Period			Frequency per million units of population		
Cause Type	**Specific Cause**	**1992-1998**	**1998-2003**	**2003-2008**	**1992-1998**	**1998-2003**	**2003-2008**
Design Fault	Design Fault	27.6	18.6	10.8	15.8	11.0	7.5
Equipment	Internal Corrosion	8.9	9.0	6.2	5.1	5.3	4.3
Fault	External Corrosion	3.1	2.4	2.4	1.8	1.4	1.7
	Erosion	7.1	4.2	3.4	4.1	2.5	2.4
	Mechanical Failure	60.5	40.8	25.6	34.6	24.2	17.7
	Mechanical Fatigue	8.7	13.0	8.2	5.0	7.7	5.7
	Mechanical Wear	5.5	4.6	4.6	3.1	2.7	3.2
	Material Defect	7.1	3.4	1.4	4.1	2.0	1.0
	Specification Problem	0.0	1.4	0.4	0.0	0.8	0.3
	Manufacturing Problem	1.6	0.8	0.2	0.9	0.5	0.1
Operational	Incorrect Fit	23.1	13.8	8.6	13.2	8.2	6.0
Fault	Improper Operation	26.5	17.0	6.4	15.2	10.1	4.4
	Improper Inspection	6.0	2.6	1.4	3.4	1.5	1.0
	Improper Maintenance	8.9	4.2	5.0	5.1	2.5	3.5
	Improper Testing	1.8	0.8	0.0	1.0	0.5	0.0
	Dropped Object	2.7	1.8	1.0	1.6	1.1	0.7
	Left Open	8.5	7.6	8.2	4.9	4.5	5.7
	Opened	10.9	3.8	2.4	6.2	2.3	1.7
Procedural Fault	Non-Compliance with Procedure	19.5	13.0	7.8	11.1	7.7	5.4
	Non-Compliance with PTW System	1.3	0.8	1.8	0.7	0.5	1.2
	Deficient Procedure	31.1	14.2	6.0	17.8	8.4	4.2
All Causes	Total	164.7	122.2	80.2	94.1	72.5	55.5

Table 12: Hydrocarbon Release Events Analysis – All Events, Including 'Minor' Severity Events.

Causation Category		Average Events per Annum in Period			Frequency per million units of population		
Cause Type	**Specific Cause**	**1992-1998**	**1998-2003**	**2003-2008**	**1992-1998**	**1998-2003**	**2003-2008**
Design Fault	Design Fault	38.0	33.8	28.2	21.7	20.1	19.5
Equipment	Internal Corrosion	14.4	19.8	17.6	8.2	11.8	12.2
Fault	External Corrosion	4.5	5.6	9.4	2.6	3.3	6.5
	Erosion	12.4	10.4	10.0	7.1	6.2	6.9
	Mechanical Failure	85.5	69.0	68.8	48.8	40.9	47.6
	Mechanical Fatigue	13.6	27.6	22.2	7.8	16.4	15.4
	Mechanical Wear	9.5	14.0	14.2	5.4	8.3	9.8
	Material Defect	9.6	6.2	4.8	5.5	3.7	3.3
	Specification Problem	0.0	2.2	0.8	0.0	1.3	0.6
	Manufacturing Problem	2.4	1.8	0.4	1.4	1.1	0.3
Operational	Incorrect Fit	32.5	29.2	26.2	18.6	17.3	18.1
Fault	Improper Operation	36.9	30.8	17.8	21.1	18.3	12.3
	Improper Inspection	10.4	7.2	3.4	5.9	4.3	2.4
	Improper Maintenance	12.4	8.6	11.6	7.1	5.1	8.0
	Improper Testing	3.1	1.4	0.0	1.8	0.8	0.0
	Dropped Object	4.5	3.4	2.8	2.6	2.0	1.9
	Left Open	11.6	12.4	11.8	6.6	7.4	8.2
	Opened	17.6	11.4	8.4	10.1	6.8	5.8
Procedural Fault	Non-Compliance with Procedure	25.8	25.0	21.8	14.8	14.8	15.1
	Non-Compliance with PTW System	2.0	1.4	2.4	1.1	0.8	1.7
	Deficient Procedure	44.5	25.6	16.8	25.4	15.2	11.6
All Causes	Total	242.5	241.6	220.4	138.6	143.4	152.6

The review appears to confirm that similar ageing issues are faced offshore and onshore for management of primary containment systems. The evidence suggests that although emphasis has been placed on more active management of ageing degradation, loss of containment incidents due to ageing still occur and may be increasing. It is perhaps reasonable to postulate that the rate of increase would be more significant if such focus had not been applied.

Extrapolating this experience to onshore plant is not straightforward because the available data does not support derivation of the equivalent trends indicated for offshore assets. However, it is considered reasonable to assume that the size of the problem will increase further as time goes on. As such, application of an equivalent focus to onshore plant, as may be achieved using a Plant Ageing Delivery Guide, could represent the first stage in bringing ageing issues under control.

4.6 Review of Previous Incident Data Analyses

A number of reports have been commissioned by the HSE over recent years to analyse incident data to inform priorities and feedback information to industry on key issues. The key reports, provided by HSE as part of this project, are reviewed below.

Semi-permanent Circular, Loss of containment incident analysis, SPC/ENFORCEMENT/90, HSE, May 2004

This SPC summarises the findings of a project, which analysed approximately 800 HSE-investigated loss of containment incidents in the onshore chemicals sector.

The project was set up to try to make better use of operational intelligence by analysing HSE-investigated dangerous occurrences and accidents between 1991 and 2002 that led to a loss of containment. The information was used to inform intervention strategies in HID and was considered to be of general interest to inspectors. The project was carried out by HSL for HID CD2B.

The main findings were that:

- 64% of incidents occurred during normal operations and 15.6% during maintenance;
- There was a range of direct causes of the incidents with inadequate isolations (10.9%), overflow (10.2%), and runaway or unplanned chemical reactions (9.6%);
- The primary risk control systems failings were maintenance (27.2%) plant & process design (25.8%), and operating procedures (24.4%).

Analysis of the data presented in the report by causation type gives:

Table 13: SPC/90 Data Analysis by Causal Type.

Causation Category	Percent
Human/ Procedural Causes	28.6%
Design and Installation Causes	6.4%
Integrity Causes	23.3%
Loss of Control	31.6%
Other	10.0%

The ‘loss of control’ incidents are likely to be a mixture of operational errors or shortcomings combined with EC&I failures or shortcomings.

The data analysis also includes the following categories that can be directly related to ageing plant integrity:

- Degradation of Material Properties
- Stress/Fatigue/Vibration
- Corrosion-internal
- Corrosion-unknown
- Corrosion-external
- Corrosion-under lagging

These failure categories account for 15% of the reported events.

This compares well with the 16% of incidents (57/348) reported in the MARS database associated with similar ageing plant integrity causes:

- Corrosion/erosion/stress corrosion cracking
- Fatigue/vibration
- Wear/friction

Investigation of loss of containment dangerous occurrences, SPC/Enforcement/132, HID CI4b, HSE, May 2007

This circular explains the process inspectors need to follow when investigating loss of containment dangerous occurrences on-site. From 1 April 2007 inspectors will be required to record on COIN causation factors for investigated loss of containment RIDDOR reports. Loss of containment dangerous occurrences (DOs) are those events reported to HSE under RIDDOR, and correctly coded against the relevant DO categories. The DO categories to be used are listed in the document.

This document does not contain an analysis of any data, but will be useful in Phase 2 when considering how the current HSE databases could be improved to monitor issues such as ageing plant.

Loss of Containment Incident Analysis, HSL Report, HSL/2003/07, HSE, 2003

This report presents findings from a project conducted by the Health and Safety Laboratory (HSL) on behalf of the Health and Safety Executive (HSE). The research was funded by the HSE Hazardous Installations Directorate (HID). The overall aim of the project was to provide information on incidents that involved a loss of containment in order to inform HID regarding intervention strategies.

Under the Reporting of Injuries, Diseases and Dangerous Occurrences Regulations 1995 (RIDDOR), employers and the self-employed are required to report certain work-related diseases, accidents and dangerous occurrences to the Health and Safety Executive (HSE). Dangerous Occurrences include incidents leading to a loss of containment. In the chemical and petrochemical industries the loss of containment of a hazardous substance has been the main factor in a number of major incidents.

A sample of 718 investigations into loss of containment incidents were identified from approximately 2,500 investigations, provided by HSE of accidents, incident and dangerous occurrences, subject to their containing enough detail to produce a profile of the occurrence. The sample was selected from across an 11 year time period, from 1991 to 2002. The advantage of sampling over a wide time period is that the incident profile that is developed should be more representative.

The data analysis from this report was added to in 2004 and formed the basis of SPC/ENFORCEMENT/90. Some additional detail is provided into the data, but the key findings are in line with SPC/ENFORCEMENT/90.

Findings From Voluntary Reporting of Loss of Containment Incidents 2004/05, HSE, Hazardous Installations Directorate, Chemical Industries Division, HSE, September 2005

During 2004/05 HSE and the onshore chemical and major hazard industries collaborated in the collection of causation information and lessons learnt from loss of containment incidents reported to HSE under RIDDOR. This was a voluntary scheme aimed at collecting information on the underlying causes of loss of containment events. The aim being to identify common failure mechanisms that feature in chemical incidents. As part of that initiative participants were asked to provide a lesson learnt from the incident, which they would wish to pass on to others within the sector.

Sharing such information others was a key message from the BP Grangemouth Report which recommended that:

"*Major hazard industries should ensure that the knowledge available from previous incidents both within their own organisation and externally are incorporated into current safety management systems*."

The report contains two sets of data, one for the chemicals sector (excluding refineries) and one for the refineries sector.

Main Findings for the Chemical Sector (excluding refineries):

Overview - 69 % of incidents can be categorised as either being as the result of an incorrect action by an operator (37%), or the equipment or plant failure (32%). The remaining 31% of incidents are spread across the other primary cause categories.

The underlying causes of operator error and equipment failure were:

Operator Error:

- 34% - inadequate operating procedures
- 18% - inadequate plant design
- 14% - inadequate supervision
- 12% - management of change

Equipment Failure:

- 30% - inadequate maintenance
- 28% - inadequate design

Main Findings for the Refineries Sector:

Overview: As the total number of incidents for the refineries sector is so small, it is difficult to identify emerging findings. Notably in comparison with the rest of the chemicals sector was the severity of the incident and the impact in terms of cost. Failure of pipework is the most common site of release for a loss of containment.

Primary Cause – Over a third of incidents (6) were caused by corrosion, the underlying causes of the corrosion were quite spread:

- Operating procedures – 2
- Maintenance Procedures – 2
- Selection/Management of Contractors – 1
- Plant Inspection – 4
- Management of Change – 1
- Plant/Process Design 3

Findings From Voluntary Reporting Of Loss of Containment Incidents 2005/06, HSE, Hazardous Installations Directorate, Chemical Industries Division, HSE November 2006

This presented an annual update of the data collection exercise as described in the 2004/05 report.

Main Findings for the Chemical Sector (excluding refineries):

Overview:

- 72% - of incidents can be categorised as being the result of either incorrect action by an operator (50%), or equipment / plant failure (22%);
- 28% - the remaining incidents are spread across the other primary cause categories.

The most common underlying causes of operator error and equipment failure were:

Operator Error:

- 53% - Inadequate operating procedures
- 11% - Plant Design
- 11% - Management of Change
- 11% - Permit to work

Equipment Failure

- 38% - Inadequate Maintenance procedures
- 23% - Inadequate plant design
- 22% - Inadequate planned inspection/maintenance

Main Findings for the Refineries Sector:

Overview: As the total number of incidents from the refineries sector is so small, it is difficult to identify emerging findings.

Primary Cause of Incident
Around 40% of incidents were caused by corrosion. The 3 underlying causes identified were:

- planned plant inspection – 4 incidents
- planned maintenance procedures – 3 incidents
- operating procedures – 2 incidents

Re-analysis of data for this ageing study

The data analysis presented in SPC/ENFORCEMENT/90 has been updated to include the additional data from the Voluntary Reporting exercises in 2004/05 and 2005/06. The overall data (1991-2006 except data for 2003/04 which is not reported) is presented in the following tables.

Table 14: SPC/90 and LoC Data Analysis by Cause.

Incident Cause	Percentage
Autoignition/Spontaneous Combustion	2.4%
Blockage	6.1%
Corrosion-external	1.3%
Corrosion-internal	3.4%
Corrosion-unknown	1.7%
Corrosion-under lagging	0.6%
Defective Equipment	7.9%
Degradation of Material Properties	5.0%
Drive away	0.1%
Dust explosion	0.6%
Electrical/electronic/programmable electronic system	1.1%
Erosion	0.0%
Human Error	9.6%
Impact/Dropped Object	2.6%
Inadequate Procedures	0.3%
Inadequate Isolation	9.5%
Incorrect Installation	2.8%
Inadequate Procedures	4.5%
Lightning	0.2%
Manufacturing defect	0.5%
Overflow	8.6%
Overpressure	4.9%
Procedural Violation	5.6%
Runaway/Chemical Reaction	8.3%
Static/Spark	1.8%
Stress/Fatigue/Vibration	4.2%
Unknown	3.5%
Unsuitable Equipment	2.9%
TOTAL	100%

Analysis of the data presented in these reports by causation type gives:

Table 15: SPC/90 and LoC Data Analysis by Causal Type.

Causation Category	Percent
Human/ Procedural Causes	29.3%
Design and Installation Causes	5.7%
Integrity Causes	24.6%
Loss of Control	29.0%
Other	11.1%

The ‘loss of control’ incidents are likely to be a mixture of operational errors or shortcomings combined with EC&I failures or shortcomings.

The data analysis also includes the following categories that can be directly related to ageing plant integrity:

- Degradation of Material Properties
- Stress/Fatigue/Vibration
- Corrosion-internal
- Corrosion-unknown
- Corrosion-external
- Corrosion-under lagging

These failure categories account for 16% of the reported events.

This compares well with the 16% of incidents (57/348) reported in the MARS database associated with similar ageing plant integrity causes:

- Corrosion/erosion/stress corrosion cracking
- Fatigue/vibration
- Wear/friction

5.0 The Definition of "Ageing Plant"

This review has highlighted issues of significance in plant ageing from a range of experience as recorded in incident reports. For clarity it is important to establish a practical definition of what "Ageing Plant" means in order to properly focus the Delivery Guide. This section proposes such a definition recognising the overall results of the review.

Previous work by HSE [10] defined ageing and ageing plant as:

"*Ageing is not about how old your equipment is; it is about its condition, and how that is changing over time. Ageing is 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 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."

Although this definition was largely aimed at process containment, it does capture the essence of ageing. We consider that this definition can be retained for this study and the Delivery Guide it will produce.

Overall, ageing plant is plant which is, or may be, no longer considered fully fit for purpose due to age related deterioration in its integrity or functional performance.

It is worth recognising that the original design life for chemical plant, is typically of the order of 25 years. This would place any plant commissioned before 1983 in this category – a substantial proportion of chemical and process plant in the UK probably falls within this definition. However for Electrical, Control and Instrumentation (EC&I) equipment, lifecycles are often significantly shorter than lifetimes of main plant. This is especially so for modern digital plant for which a lifecycle (start of operation to replacement) duration of 10 to 15 years may be more appropriate.

As highlighted above, there is a need to distinguish between plant that has been in place for many years, and that which is 'wearing out' such that it may exhibit a higher risk of failures or leaks. The former can be considered old or aged plant. Aged plant may be fully fit for purpose, and could be in a good condition as per its original design intent. However, aged plant may be susceptible to fatigue cycles or corrosion beyond its design basis, even if it has been well maintained. Plant life extension justifications are one way to ensure these issues are recognised and addressed.

Aged Plant may also not be in-line with current codes and standards and good practice. This may not necessarily mean the plant is not fit for purpose, but a review against current standards

[10] Plant ageing, Management of equipment containing hazardous fluids or pressure, HSE Research Report RR509, HSE Books, 2006

should be carried out to assess any differences and the implications of these. Any shortcomings could be overcome by bringing the items up to standard or introducing other (alternative) reasonably practicable measures or procedures to fill the gap.

6.0 Installed Plant Location Review

HSE have provided location data for hazardous installations in the UK. Part of the scope for this study is to determine whether or not there are any geographical variations in the occurrence of ageing incidents. This is of importance because should such variations exist it would be instructive to HSE Inspectors to understand the reasons for them and target certain aspects of inspections accordingly.

This analysis is ongoing but at this stage the results for COMAH sites are available. To properly interpret the results of a geographical analysis it is important to first establish the location of all sites in the UK. Figure 12 shows the distribution of COMAH sites.

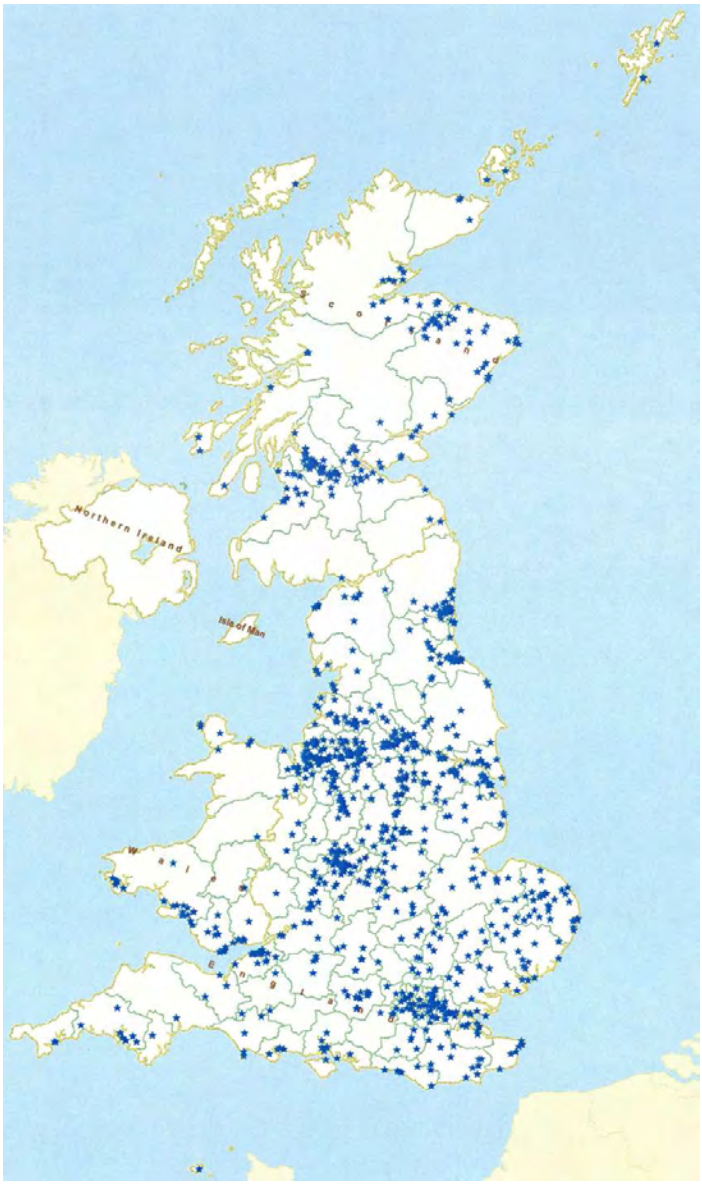


Figure 12: Distribution of COMAH Sites.

Figure 13 indicates the distribution of all COMAH incidents irrespective of cause.



Figure 13: Location Distribution of All COMAH Incidents.

Figure 13 indicates that there appear to be no specific areas of concentration of COMAH incidents given the locations of all COMAH sites shown on Figure 12. This is also shown in Figure 14 which plots the number of COMAH incidents (Data in Columns) against the background of COMAH site locations (Location dots). This shows that the distribution of incidents aligns with those areas with the highest density of COMAH sites. The data and locations are split by COMAH top-tier and COMAH lower-tier. The location of sub-COMAH sites are also shown, but no incident data is presented for these.

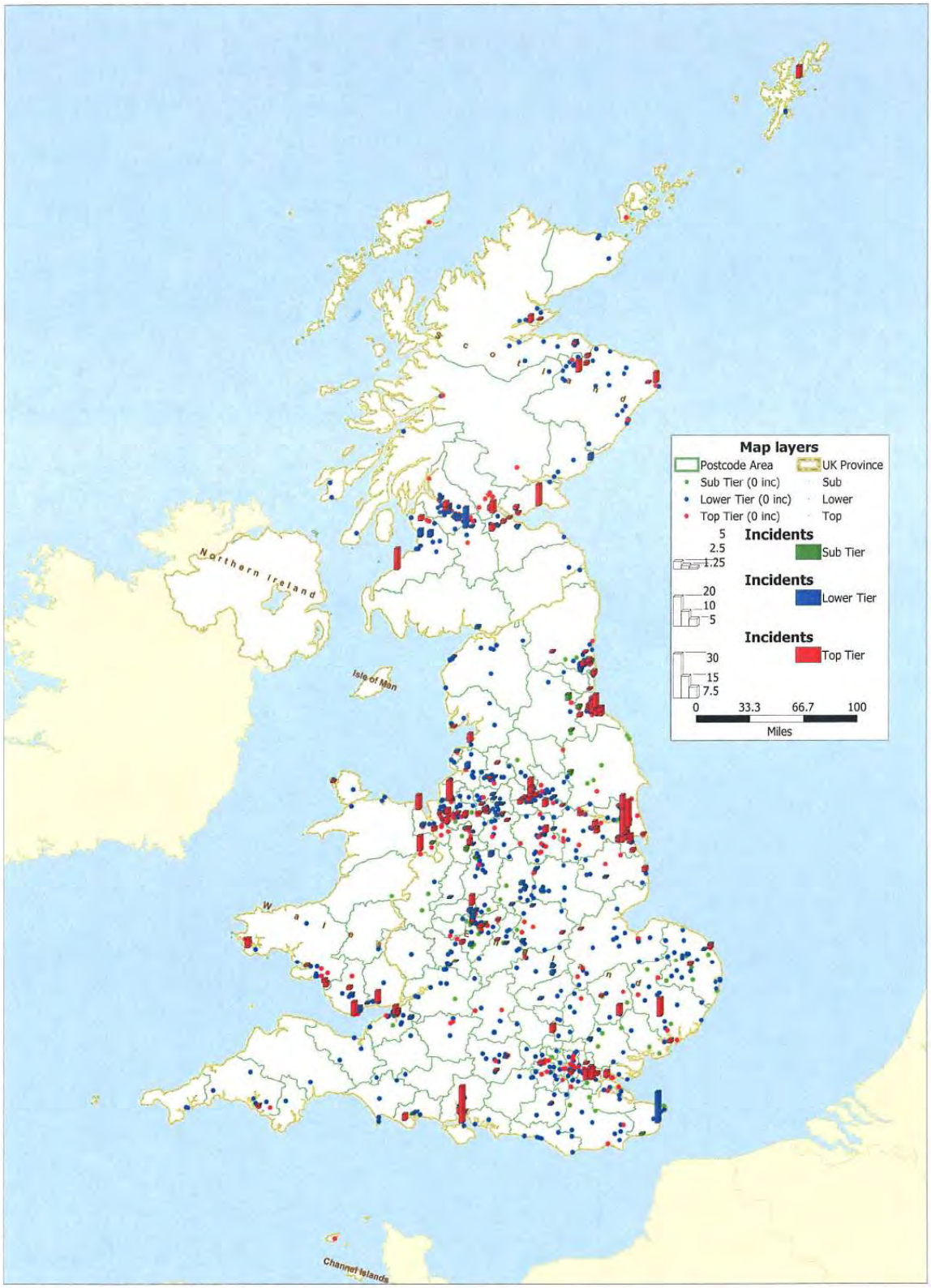


Figure 14: Location Distribution of All COMAH Incidents set against the COMAH site Locations.

Figure 15 shows the distribution of COMAH incidents that can be determined to be a result of a technical integrity failure.



Figure 15: Location Distribution of COMAH Technical Integrity Incidents.

Again, no specific variations of significance are immediately apparent in comparison with either the distribution of all incidents or the distribution of all sites. This requires confirmation by examination of changes in incident density in comparison with site density.

Figure 16 shows the distribution of COMAH incidents where it can be established that EC&I was a contributory factor.



Figure 16: Location Distribution of COMAH Incidents where EC&I was a Contributory Factor.

It is apparent that no specific geographical variation can be identified.

Figure 17 indicates the distribution of COMAH incidents that can be attributed to plant ageing.



Figure 17: Location Distribution for COMAH Incidents Related to Plant Ageing.

No specific geographical variations are apparent.

The analyses conducted so far in this study are limited in that they only consider COMAH sites. The graphical representations are also not able to display the numbers of incidents in any given location. For reference the following description of the statistics shown on Figures 12-17 is provided:

Table 16: Statistics of all COMAH Sites and Incidents.

COMAH Tier	Sites	Incident sites	Total incidents
Top	385	154	572
Lower	704	84	170
Sub	115	27	34
Total	1204	265	776

The RIDDOR database (version 2) consists of 2812 incidents. There are a total of 776 incidents occurring on 265 COMAH sites in the database and the breakdown by COMAH tier is shown in Table 16. There are clearly many sites with multiple incidents.

There are 298 COMAH incidents which can be classified as integrity related. From these only 96 have an attributable cause. The incidence of various causative factors are shown below.

Table 17: Incidence of factors in 96 integrity related incidents.

Factor	Occurrences
Corrosion/erosion/SCC	19
Fatigue/vibration/wear	5
Human error/management failure	54
Control and instrumentation	27

General observations from the analysis are:

- For the limited data set represented by incidents at COMAH sites no geographical variations are immediately apparent.
- A futher analysis of incident density would be instructive in confirming the above observation.

Extension of this analysis to the full database of UK incidents would provide an improved understanding of whether or not geographical variations in the type and frequency of ageing related incidents exist.

7.0 Summary of Relevant Plant Ageing Questions

The analyses presented in the above sections have identified a number of questions of relevance to plant ageing issues. A summary of the questions is provided below.

7.1 Primary Containment Systems

- Are age-related damage mechanisms identified and assessed in the plant inspection and maintenance plans ?
- Are appropriate inspection and maintenance techniques applied that are effective in management of age-related degradation ?
- Is corrosion, both internal and external, monitored and trended ? How are the results of the monitoring used to influence future integrity management actions ?
- Is the potential for cracking understood ? Do justifications exist for planned actions, or lack thereof, to manage cracking ?
- Are changes to the process assessed in respect of impact on plant integrity over short, medium and long terms ?
- Does the installed equipment meet the requirements of modern design standards ? If not, are the key differences between the original standard and its modern equivalent understood and the potential impact for plant integrity assessed ?

7.2 EC&I Systems

- Is the EC&I equipment “ageing”?
- Do the Operators understand the safety significance of their EC&I equipment?
- Are the Operators planning for the likely replacement of at least some of the EC&I equipment during the lifetime of the whole plant? Are they aware of the technical and resource issues?
- Are the Operators aware of issues surrounding safety and “cost of ownership” of modern digital safety-related equipment?
- Do the Operators have adequate arrangements for Maintenance and Procurement of modern EC&I equipment?
- Do the Operators have adequate arrangements for Management of Change (MoC) when replacing older (typically analogue) EC&I equipment with new (almost always digital) equipment? This includes:
    - the MoC process itself,
    - Functional Safety Management (FSM),
    - Safety Integrity Level (SIL) qualification,
    - software Verification and Validation (V&V),
    - software configuration management, and
    - project management

- Basic information on installed EC&I systems (What type of equipment is there currently on site?)

- EC&I lifecycle issues (What is the typical lifecycle of EC&I equipment? What ageing processes are there? What are the potential business impacts of large refurbishment projects? Can ageing be mitigated?)

- Safety aspects of modern digital equipment (What are the key safety issues with modern digital equipment?)

7.3 Management Systems

- Do management systems recognise the existence of aged plant and ensuring suitable attention is paid to this (identification and awareness of the issue) ?

- Are mechanisms in place to identify new codes, standards, lessons learnt, or good practice and to review these to check the implications for existing plant ?

- Do Management of Change arrangements exist to identify and assess changes to plant, structures, processes or operating / maintenance regimes which could invalidate the original design or lead to accelerated ageing ?

- Are there systems to gather information from inspections, surveys, audits, maintenance systems, incidents reports, etc and analyse these to help identify any trends or issues AND feedback mechanisms to update these arrangements (e.g. change inspection frequency) if an issue is identified or suspected ?

- Do these inspections etc extend to civil and structural features of the plant and safeguards eg flood control embankment, ground subsidence, integrity of paved areas, drainage systems and bunds, buildings, walls, plant supports, pipebridges, pits and culverts, tall structures, etc ?

- Are there Management of Change / Competency Assurance arrangements to ensure key skills, knowledge and experience with aged plant is retained, especially as older personnel retire or move on or when reducing manning levels or when outsourcing maintenance work for example. Are there suitable qualified resources available to identify and address ageing issues, i.e. competent corrosions engineers, structural/ mechanical engineers, EC&I specialists, etc ?

7.4 Structures

- Do inspections and maintenance procedures extend to civil and structural features of the plant and safeguards, for example
    - flood control embankment
    - ground subsidence
    - integrity of paved areas
    - drainage systems and bunds
    - buildings
    - walls
    - plant supports
    - pipe-bridges
    - pits and culverts

- tall structures

7.5 Safeguards

- Are there hazard or risk assessments in place and do these identify all the safeguards required?
- Are safeguards provided to meet these requirements?
- Are the safeguards adequate in terms of their capacity, speed of response, coverage etc to achieve the required functionality?
- Are the safeguards adequate in terms of their availability, reliability, survivability and endurance to provide a high probability of working when required?
- Are the safeguards recognised as HSE critical systems and included in the maintenance, testing and inspection arrangements?

8.0 Conclusions

The following conclusions are drawn:

8.1 General

- Between 1996 and 2008 it is estimated that there have been 173 loss of containment incidents reported in RIDDOR that can be attributable to ageing plant. This represents 5.5% of all loss of containment events. The limited information provided in RIDDOR about the underlying causes means that it is difficult to identify which events may be age related: the actual number could be much higher than that quoted here.

- Across Europe, between 1980 and 2006, it is estimated that there have been 96 incidents reported in the MARS database relating to major accident potential loss of containment which are estimated to be due to ageing plant. This represents 28% of all reported 'major accident' loss of containment events in the MARS database and equates to an overall loss of 11 lives ,183 injuries and over 170Million € of economic loss.

- As the MARS data provides the more detailed and comprehensive insight into the incidents and causal factors and is specifically related to potential major accident hazard events, it is considered that this represents a more realistic indication of the extent and severity of ageing plant and its contribution to major accidents. This leads to the conclusion that ageing plant is a significant issue.

- Overall it can be concluded that plant ageing does constitute a threat to health and safety performance of hazardous installations onshore in the UK. Within the uncertainties of the review conducted a reasonable statement to describe the size of the issue is "60% of incidents are Technical Integrity issues and 50% of those are associated with ageing of one type or another".

- A useful development in reporting of incidents would be to include a simple checklist focused on causation, i.e. recording of contributing factors that emerge from the incident investigation. For the purposes of future monitoring and trending it might be worthwhile considering extending recording of causation factors to include specific ageing issues.

- A review of offshore loss of containment data appears to confirm that similar ageing issues are faced offshore and onshore for management of primary containment systems. The evidence suggests that although emphasis has been placed on more active management of ageing degradation, loss of containment incidents due to ageing still occur and may be increasing. It is perhaps reasonable to postulate that the rate of increase would be more significant if such focus had not been applied.

- Extrapolating offshore experience to onshore plant is not straightforward because the available data does not support derivation of the equivalent trends indicated for offshore assets. However, it is considered reasonable to assume that the size of the problem will increase further as time goes on. As such, application of an equivalent focus to onshore plant, as may be achieved using a Plant Ageing Delivery Guide, could represent the first stage in bringing ageing issues under control.

- There is a need for a clear definition of ageing plant. ESR proposed that the definition provided in HSE Research Report 509 on Plant Ageing (2006) is retained. Although this definition was largely aimed at process containment, it does capture the essence of ageing and has been adopted for this project.

- Analysis of location data has indicated that for COMAH sites no immediate variations in geographical distribution of ageing incidents exists. Further analysis is required to confirm this. Extension of the analysis to include all UK incidents would provide an improved understanding.

8.2 Primary Containment Systems

- Corrosion remains a significant issue.
- Failure mechanisms that can lead to rapid failure but are still significantly influenced by age, e.g. fatigue, stress corrosion cracking, CUI etc, are a significant issue.
- Planning of inspection and maintenance activities significantly influences the results, i.e. failure to plan for ageing issues is apparent in the databases.
- The effect of the process on plant ageing is not fully understood, i.e. changing the process or increasing throughput is not evaluated in terms of the effect on the ageing rate.

8.3 EC&I Systems

- EC&I issues are a significant factor in around 2% of major accidents.
- EC&I accidents that could have been prevented by improved maintenance and testing represent a significant percentage of all accidents caused by EC&I issues.
- The biggest single factor in all EC&I failures is associated with Level Detection, often resulting in vessel overfill and loss of containment. The vast majority of these failures are associated with inadequate maintenance and testing.
- Design issues account for a significant proportion of EC&I associated failures – although these are not usually associated with ageing issues.
- Other significant causes of EC&I failure include Loss of Site Power, Lightning/Earthing and Software failures, including examples of issues caused during upgrading to modern DCS control systems.

- There is a need, on all high-hazard plants, for very firm links between:
    (i) the Safety Case (identifying the Safety Critical Elements) and
    (ii) the Maintenance Inspection and Test (MIT) schedule (taking each and every SCE and going right down to individual instruments, logic elements and output devices, also addressing potential initiating events like loss of

supplies and lightning strike, and defining specific test requirements and frequencies).

- The MIT schedule, based on the Safety Case, needs to be matched with KPIs measuring the backlog of safety-related maintenance, to make sure that management can see that the appropriate MIT work is being completed.
- All high-hazard plants should include in their safety cases a clear demonstration that:
  (i) the design has considered safety implications of loss of electrical supplies (both locally and site-wide)
  (ii) there is adequate lightning protection (which is maintained adequately),
  (iii) the single failure criterion has been taken into account.

8.4 Management Systems

- Procedures, including Management of Change, were highlighted as being an influence in 43% of the Management Systems incidents. For ageing plant this could develop from failure to update operational process procedures as plant and equipment life is extended or failure to update procedures that may protect plant from the effects of ageing such as improving maintenance regimes, inspection and audit schedules.

- Standards were identified in 24% of the incidents that indicated some level of management system failure; this included the availability of a competent workforce. The issue that arises here with ageing plant is the failure to maintain operational knowledge of plant and equipment due to turnover of staff. The lack of good training and development programmes linked with competency testing will contribute to reduced knowledge in the workforce operating ageing plan, and equipment. This applies to both own staff and contractors.

- Hazard and Effects Management weaknesses were recognised in 18% of the incidents identified but yet again none of these could be directly identified with ageing plant. The relevance of H&E management to the ageing plant issue is where there is a lack of any risk review process in place to identify changed hazard scenarios throughout the plant and equipment life. The issue is particularly relevant to ageing which could be due to environmental or changed operational exposure affecting the plant, and not necessarily to the ultimate age of the plant.

8.5 Structures

- The incident data does not support any general conclusions regarding ageing of structures. However, it is not clear to what extent ageing of structures is taken into account within the plant inspection and maintenance schemes given the often safety critical nature of the structure's function.

8.6 Safeguards

- Few descriptors in the databases give any details on what safeguards were meant to be present and which, if any, failed and why. As such the data cannot be relied on to provide a robust indication of the extent to which ineffective safeguards may contribute

to major accidents, nor can it indicate the extent to which ageing may have contributed to the safeguard failures or shortcomings.

- However, the data does provide a number of examples that suggest specific safeguard failings that may be age related. It is not clear how many of these are entirely age related, but they do indicate a lack of appropriate testing, inspection or maintenance, or violations of safety arrangements over long periods of time.

- The extent of age related shortcomings in safeguards systems is difficult to assess from the limited data available. The number of potential safeguard 'ageing' related problems from the analyses of the MHIDAS and RIDDOR data are comparable; both data indicates that these represent approximately 0.4% of all events. This is low, and probably is a reflection of the reporting which tends to focus on the primary causes of the leak or incident rather than any secondary or contributory failures. The MARS data contains more comprehensive event descriptions, and this is reflected in the increased probability of age related safeguards issues in the data, of the order of 4% of all events. It is considered that the true figure could be significantly higher than this, as a high degree of under-reporting is likely in terms of the role of safeguard systems in these incidents.

9.0 Next Steps – Phase 2

The following steps are currently envisaged for Phase 2 of this study:

- Complete a detailed assessment and review of all significant identified plant ageing issues. Detailed descriptions of the ageing phenomena in terms of causes and effects will be developed.
- Identify physical means by which all relevant plant ageing phenomena can be detected. Detailed descriptions of detection techniques will be developed.
- Work closely with HSE Specialists and HSE Inspectors to:
    - Check the basic set of questions presented in this report is complete.
    - Refine the questions and identify specific questions for specific plant types, e.g. chemical plant, refineries, COMAH sites etc.
    - Test the questions by applying a series of scenarios, perhaps based on MARS incidents, to determine whether or not the ageing effects could have been detected and prevented.
- Develop the Plant Ageing Delivery Guide question set.
- Develop the geographic analysis of plant ageing incidents to determine if the distribution of ageing effects is as expected. Any apparent anomalies will be raised for discussion with HSE.

Appendix 1 Possible Ageing Plant Topics

The range of issues presented in this Appendix originates from a range of HSE Specialists following a request for their views on plant ageing issues at the start of the study. These were of significant value in forming the lists of identified issues that were applied during the data review.

Electrical, Control & Instrumentation Discipline

a. Ageing of electrical power distribution

Electrical power distribution systems, including the provision of emergency power generation to control such plants on loss of grid supplies. There have been a significant number of incidents arising out of power loss on COMAH sites.

b. Obsolete Ex electrical equipment

Control systems in use that have now become obsolete and are no longer supported, including programmable (PLC, DCS and other bespoke PC based systems) and non programmable (pneumatic, electronic) systems designed and commissioned in the past. Some of these systems can be fairly new and are no longer supported by the supplier. Duty holders may also have no spares available either. The duty holders should be looking to upgrade these systems so these can be maintained and supported by the suppliers.

c. Obsolete computer hardware

Systems tend to become obsolete after 7 years or so when the next generation hits the industry and after this period the hardware components become increasingly difficult (and expensive) to resource. This can be a significant issue for the medium/small users who may lack the money to pay for specialist spares, or lack internal expertise. They may run process control computers for 15-20 years or more and have to resort to obtaining spares from third parties or attempting repairs in house with unknown quality resulting.

d. Obsolete computer software

Software does not wear out but it does need to be maintained because changes take place on a regular basis (process development often means changes, new peripherals (no plug/play on these older systems!), better displays etc; often its making changes to the process which are enabled by the computer). As time moves on, languages become obsolete and it can become increasingly difficult to get people who are familiar with a particular programming language (system, user or both) ---it's the competence that's becoming obsolete but it can have plant wide effects if mistakes are made.

e. Obsolete instrumentation

Materials for instruments can show problems of premature ageing in some types of plants. All instruments are based on sensors to carry out a measurement and these sensors can be a fraction of a millimetre in order to work; a pressure transmitter would be a typical example. Specifying materials for these is very different from a vessel where you can have a corrosion allowance of a few millimetres. Failure can have two dimensions; a functional failure which means the instrument gives wrong readings and/or a loss of containment if the body is breached (limited to an inch or so in size). The selection of materials for such instruments often depends on years of development and where this has happened, the results are often good. But there are some instances where you can't get the experience because the process and chemistry changes on a frequent basis; one example is the manufacture of herbicides/insecticides where products are regularly reformulated to overcome species building up resistance and you can't run on a specific formulation for long enough to get the experience; it can be made worse because quite a few of these compounds rely on chlorine, fluorine, sulphur containing (and so on) molecules to get their selectivity, all of which require some aggressive chemistry. And they are mostly batch processes with constant cycling temperatures which does not help.

f. Premature EC&I equipment failure

Most of the problems with premature failure are associated with failures in the company's approach to original design and/or PPM and inspection/testing. Some common EC&I equipment failures include:

- Corrosion of EX equipment, especially in salt water jetty areas (nearly all these sites have some sort of corrosion problem)
- Fouling of sensors - common examples include:
    - Level interface controllers: Fouling means unreliability- maintenance team revert to tri-cock measuring system, which basically requires manual valves being opened at levels to see if hydrocarbons present.
    - Oxygen analysers (and others) fouling a common problem in batch chemistry applications
    - PH sensors contamination problems/failure to recalibrate with suitable buffer solutions
    - Gas detector contamination (used to be a common problem with pellistor type).
- Sticking control valves or ESDs. A number of sites have experienced problems with this throughout the years.
- Poor support of electrical cabling/equipment due to support framework corrosion, (e.g. tray/trunking/unistrut supports).
- Water ingress usually due to wrong IP rating or corrosion problems.

g. Better Process Control Strategies (i.e. recognise and design out the problems)

In the chemical industry designated safety related systems are usually subject to PPM and periodic testing, however, often process control systems are only subject to reactive

maintenance/testing. Thankfully there has been some change to this attitude in recent years with more focus on lifetime plant integrity; however, it is still a common problem.

A good HAZID/HAZAN should recognise that process control systems will fail and processes will exceed operating envelope specifications. Historically HAZOPS were the most common tools used to do this. This results in the basic specification for a safety related system (e.g. process alarms/trips, Safety Instrumented Systems basic spec, mechanical relief systems etc.)

However, this does not really deal with how a process control strategy should be designed to optimise production and also to minimise process upsets. It is often the case that the full range of process disturbances are not recognised within the design specification of the process control strategies. This is often linked back to lack of availability of a good process simulation model, either through a real life prototype or through a mathematical model (nowadays usually approached through software). (e.g. MATLAB/Simulink). Even when this area has been given some consideration, at best, optimisation of the strategy is usually based on known feedstock characteristics (e.g. chemical constituents, flow rate, pressure, temperature etc.) It often does not also take into account deviations that may be caused due to any changes of these variables. This can lead to process upsets, which in some cases can also lead to greater stresses on plant and equipment and impingement on designated protection systems, or if none in place, a direct loss of containment.

In the petrochemical industries, the vast majority of automatic control is based on PID and Cascade control. These are often set up during commissioning using some basic rules with limited process information. There are a number of auto tuning systems available. However, in general, the full range of disturbances is not considered. There are some advanced control strategies also used. However, to date most of these are used to optimise product yield. I haven't come across any serious application to help with the full range of process disturbances, most of them default to PID when "out of range".

Mechanical Engineering Discipline

a. Stress Corrosion Cracking in jacketed reactors and elsewhere.

SCC is a mechanism that is often missed or poorly dealt with by inspection bodies - 'correct' management of this mechanism will depend very much on the particular situation; a reactor with a water reactive material and a relief system not designed to cope with the consequences of water ingress would be a big concern, whilst a low pressure reactor with benign contents would be much less of a concern. In larger vessels (e.g. columns) the main concern is likely to be structural stability.

b. Cycle fatigue of storage tank floor plates

Large atmospheric storage tanks tend to suffer low cycle fatigue in the floor plates. There appears to be nothing explicit in the design codes that defines basis for floorplate design in terms of cyclic life, yet there are suggestions (books and courses) that the design basis is 25 years at 1 cycle per week (1300 cycles). If this is the case (and it's clear that the floor plate will be subject to cyclic stressing with fill/empty cycles), the absence of anything authoritative could well lead to older tanks straying beyond the original 'design life' without anyone appreciating that fatigue has/will become a real issue.

c. Performance of Competent Bodies

There are concerns around the performance of competent bodies in terms of identifying degradation mechanisms, carrying out effective inspection and taking appropriate action. It would be useful to include something on what Regulatory Inspectors should look for in this area as indicators of a poorly performing Competent Body.

HSE has come across companies who have made a positive decision to embark on a revalidation exercise to extend the operational life of assets. This is sold as a positive step, but is it really as good as it sounds? One organisation has focussed on sorting out CUI issues (which should already be being managed) rather than, as one would have expected, for example, looking at cyclically loaded vessels and seeing where they sit within their design lives and perhaps scheduling some fairly extensive inspection to 'fingerprint' their current condition and hence justify extended operation and define the future inspection programme.

d. Fatigue of chemical batch reactors commonly found in the pharmaceutical sector and some other specialised chemicals

They are generally in batch or campaign duties, so are regularly cycling both at temperature and pressure. Pressures are normally low (perhaps only 1barg or less, but they have low design pressures also). Temperatures can be in the order of 100/200degC, but of course cycle from ambient. Most of the operators visited had no idea if these vessels could be subject to fatigue loading or not, they don't count cycles of operation and at best can only have a rough guess.

e. Failure of pipework/pipeline supports

A common issue of concern, particularly when the pipework is carrying dangerous or corrosive substances

Regulatory Discipline

Part of the research could look at a range of operators who are managing ageing plant to:

- See how it was discovered.
- Who discovered it.
- What was the common easy to spot things.
- What were the harder to spot things.
- How they managed it; derated, increased periodicity/depth....etc.
- Outcomes from managing plant in terms of being able to keep plant operating safely.

(NB: Need to be mindful of any duplication with RR509).

This approach would establish a wider picture of what's happening and capture straightforward steps that other operators have taken. It would also involve and appeal to industry so that the project could be more widely used (i.e. not just for HSE ownership but for industry too). The project output could be in a form that may be shared more widely, so that it is owned by industry and HSE, with HSE not just left as the sole custodian (e.g. the guidance could be presented on the HSE Website and not just be internal guidance).

Could part of the research work contribute to the regulated and the regulator sharing a common view of ageing plant?

Appendix 2 Non-Metallic Materials Failure Mechanisms

The failure mechanisms in composite components in the oil and gas, chemical and process industries are well understood. There have been numerous studies looking at the sequence of damage events leading to failure and the relevant fracture mechanisms.[11] [12] [13] [14] [15]

The failure mode of GRE pipes in oil and gas applications and many chemical applications is resin dominated; and damage accumulation is by resin cracking with no fibre breakage. The failure mechanism of undamaged GRP pipe is *weepage (***Figure 18:),** a gradual seepage of internal contents uniformly over the pipe length. The failure is caused by internal pressure (plus also axial loads). The fluid path through the pipe wall is the combination of mostly through-thickness matrix cracks running parallel to fibres with some delaminations. Eventually this can lead to formation of fluid paths through the material to the outside surface.

[11] Hogg, P. J., and D. Hull, "Micromechanisms of Crack Growth in Composite Materials under Corrosive Environments," Metal Science, pp. 441-449, August-September 1980.

[12] Ageing of composites in oil and gas applications, S Frost; Ageing of Composites, Ed. Rod Martin, Chapter 14 p 375-395, Woodhead publishing, ISBN 978-1-84569-352-7, 2008

[13] Ageing of composites in the chemical process industry,R Martin; Ageing of Composites, Ed. Rod Martin, Chapter 17 p 375-395, Woodhead publishing, ISBN 978-1-84569-352-7, 2008

[14] AG Gibson, The cost effective use of fibre reinforced composites offshore. University of Newcastle Upon Tyne, HSE Research Report 039, 2003

[15] C.M. Renaud and M.E. Greenwood, Effect of Glass Fibres and Environments on Long-Term Durability of GFRP Composites.



Figure 18: Weepage failure of a GRP pipe

The main mechanical degradation is matrix cracking (**Figure 19:**) where lots of transverse microcracks form in the central ply in response to strain or loading. Delaminations and through-thickness matrix cracks result from the coalescence of matrix micro-cracks and interfacial debonding. The creation of these micro-cracks and interfacial de-bonds are accelerated due to the combined effects of the ageing process and applied loads when compared to short term failures through the sole application of pressure. However, the failure mode remains unchanged.

Other relevant mechanisms include impact damage, degradation of adhesive bonds, disbonding, flange cracking and environmental ingress.

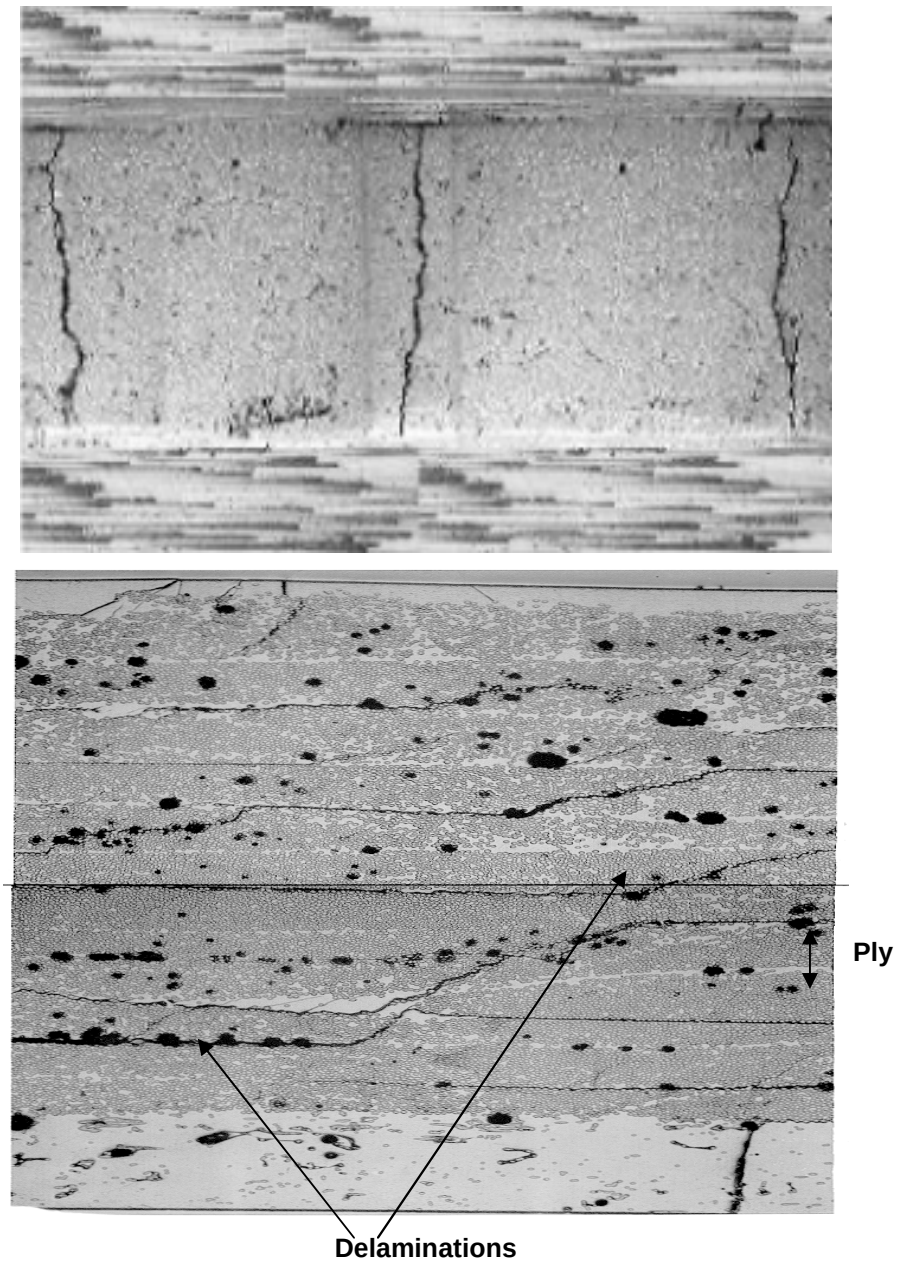


Figure 19: Microstructure of GRP pipe weepage failure

Impact damage results in delaminations within the wall of a GRP pipe. Severe impacts can cause the pipe to weep on application of pressure local to the impact zone (**Figure 20:**). Lower energy impacts can cause the pipe to weep at lower failure pressures than undamaged pipe

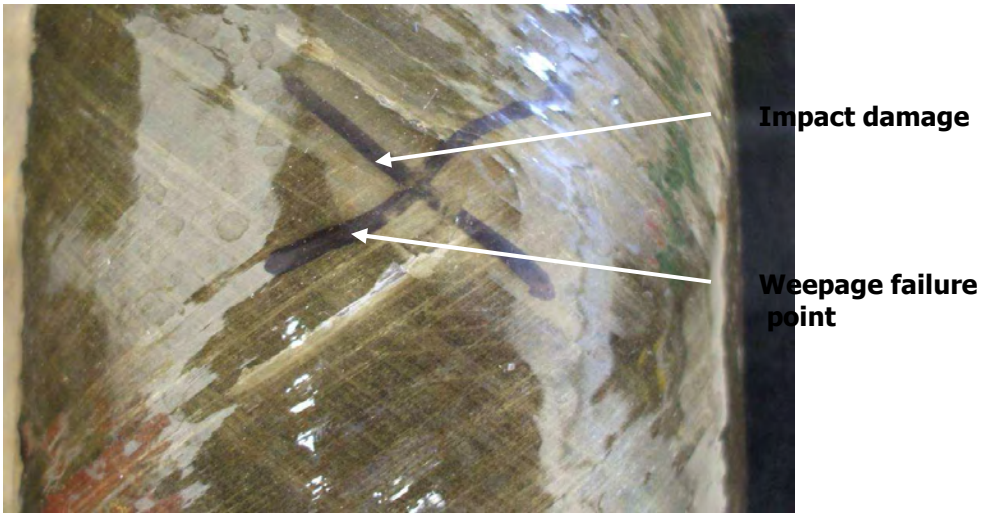


Figure 20: Weepage (local) failure of an impact damaged GRP pipe

Microstructure of the pipe wall consists of all plies with ply through thickness matrix cracks. Both short term and long term failures from a mechanism perspective are similar in appearance, i.e. weepage. Microstructure of the pipe wall at failure involves both matrix cracks and delaminations. The presence of delaminations provides more paths for the fluid to flow implying fewer through-thickness matrix cracks are required to complete the fluid path through the pipe wall

Chemical attack (in Oil and Gas applications) primarily involves reduction in matrix properties. It causes a reduction in strength and stiffness of the resin resulting in weepage at lower pressures. Chemical attack can in severe cases dissolve the resin leaving bare, exposed fibres. Chemical ingress also lowers the glass transition temperature of the resin. In chemical and process applications the possibility of fibre damage or stress corrosion cracking (SCC) of the fibres should also be considered. The micrograph in (Error! Reference source not found.) show considerable fibre cracking due to stress corrosion cracking
Stress cracking only occurs in glass fibres in low or high pH service fluids.
For medium pH service fluids the strain to cause stress cracking of glass fibres is about 0.7%, significantly greater than normal design strains, of the order of 0.25%. In most oil and gas applications the strains are too low to cause SCC.

For Oil and Gas applications the chemicals that are present generally will not cause fibre degradation. Chemical attack is a long term degradation process as it takes time for the chemical species to absorb into and diffuse through the GRP. To prevent chemical attack of GRP often a chemical resistant layer is used in the form of an inner liner (protective layer)

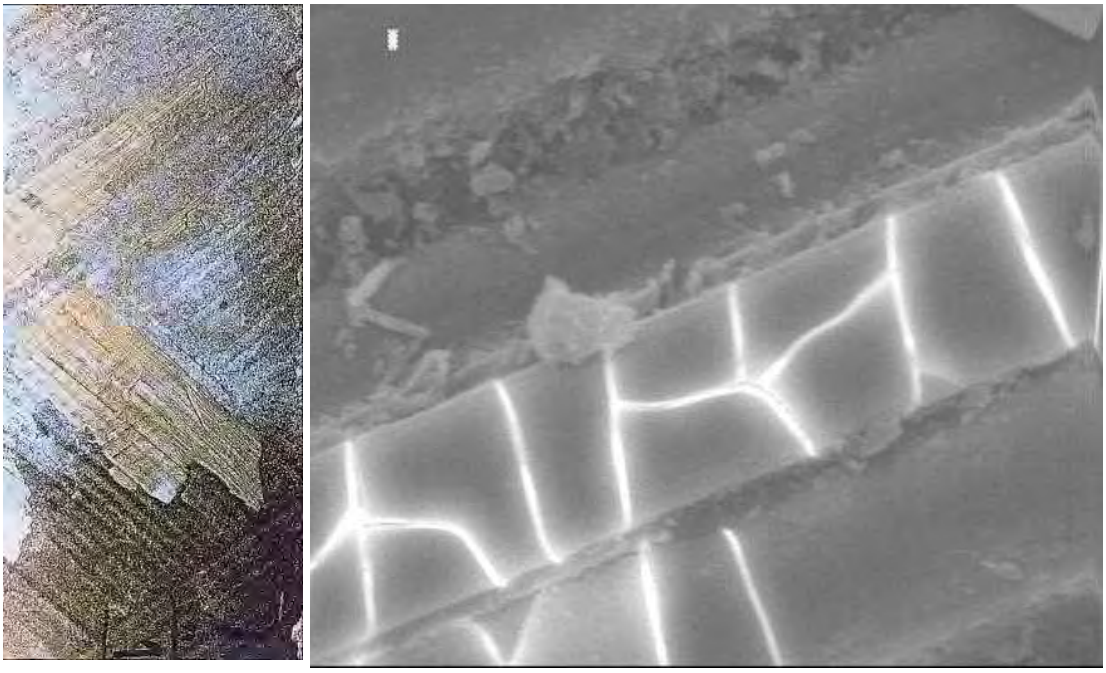


Figure 21: Examples of chemical attack. Left, Breakdown of inner liner due to chemical attack; right, SEM electron image of glass fibres from a filament wound pressure vessel, following sulphuric acid attack.

For composite joints the most common failure modes are adhesive bond failure or flange cracking both potentially leading to leakage of the process fluid. Cracking issues in flanges and joints after installation are often due to overstressing, poor alignment or poor joint preparation.The adhesive in bonded joint ages and degrades by similar mechanisms to the matrix.

Butt and wrap joints fail along the interface between the GRP pipe and the over-wrapped joint **(Figure 24:).** The failure is caused by pressure acting on the wrapped joint and will be weepage of internal fluids along the interface. This is the common failure mode for most bonded systems; the bond will fail before the composite component. Adhesively bonded joints will fail through pull out of the connections due to axial loads. The most common cause of failure is either lack of adhesive or poor quality bonding of the adhesive to the GRP joint faces (**Figure 25:**).

The failure mode of internally pressurised lined (thermoplastic) composite components is burst. The GRP will crack under load but weepage will not occur as the liner prevents weepage of the contained fluid. Ultimately the GRP component will fail when the fibres can no longer withstand the applied load.

A growing application of GRE and CFRP composites is in composite overwrap repairs on steel pipework. For through wall defects the composite repair will fail along the interface (see photograph). The failure mode is weepage of internal fluid caused by internal pressure. The failure is along the interface and not failure of the composite repair material

Additional examples of service failures in GRE pipework from the onshore petrochemical industry are shown in are shown in (**Figure 26:**)



Figure 22: Failure of a GRP lined bottle showing burst failure (significant fibre breakages)



Figure 23: Location of failure for a composite overwrap repair

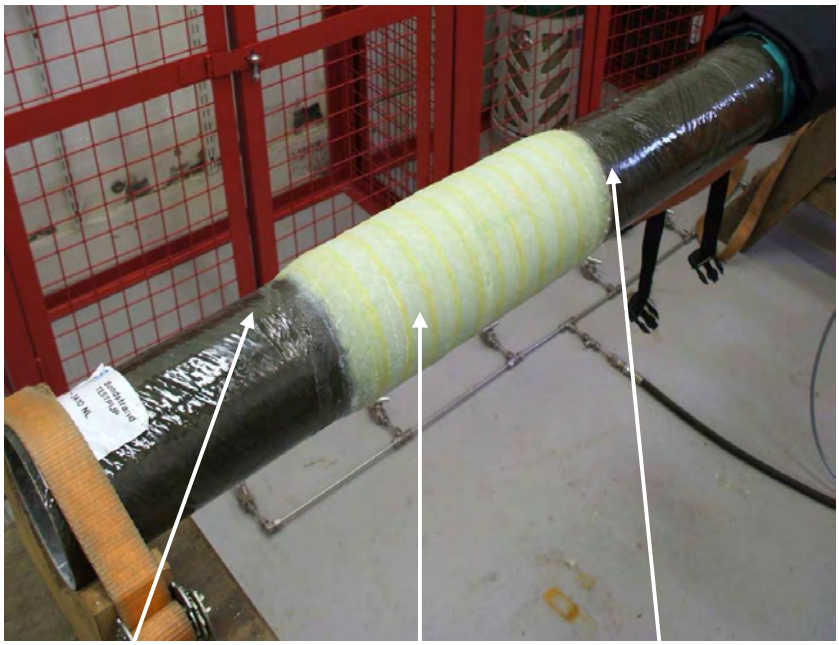
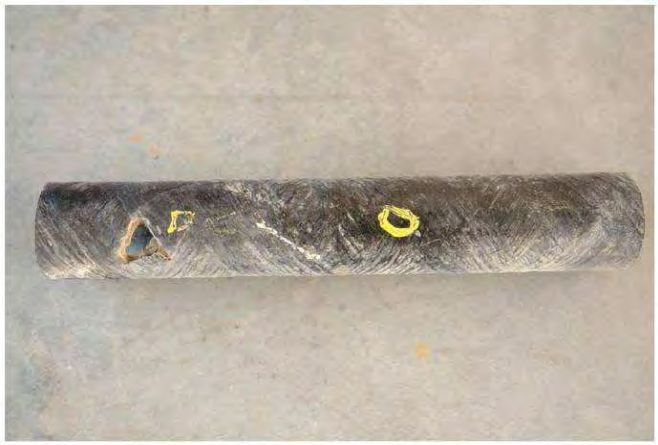


Figure 24: Top, example of an adhesive bond failure of GRE pipework in service. Bottom, butt and wrap joint showing the interface, the normal location for bond failure.



Figure 25: Photo of the female face of an adhesively bonded joint showing lack of adhesive (dark areas)



GRE Fire Water System Pipe damaged in service (through wall defect)
OD 60 mm WT 4 mm Length 360 mm



GRV SO_2/ H_2SO_4 acid one year in service - weeping from manufacturing defect
OD 65 mm WT 5.6 mm length 385 mm



GRP Oily waste – 5 years service, weeping (from impact damage).
Gulf Eternit Industries Co. Ltd (FPI Dubai ?) Date 15-7-99 ?
OD 159 mm WT 5.5 mm length 975 mm



AMIANTIT/Ameron JV Bondstrand Ltd, 1.5" and 4" HD flanges ANSI B16.5 Cl-150
Reverse osmosis RTR spools – pipes weeping during hydrotest

Figure 26: Examples of service failures in GRE pipe.

Appendix 3 EC&I Incident Examples

There is a very large body of case studies involving EEC&I failures. A very brief description of a small selection of interesting and relevant accidents and incidents is presented below.

The following sections present

- brief details of the EC&I aspects of the Buncefield, Texas City and Ariane 5 accidents.
- brief details of some incidents which were of minor consequence but which could potentially have been significant in different circumstances.

Buncefield – EC&I aspects

In the early hours of Sunday 11th December 2005, a number of explosions occurred at Buncefield Oil Storage Depot, Hemel Hempstead, Hertfordshire. At least one of the initial explosions was of massive proportions and there was a large fire, which engulfed a high proportion of the site. Over 40 people were injured; fortunately there were no fatalities. Significant damage occurred to both commercial and residential properties in the vicinity and a large area around the site was evacuated on emergency service advice. The fire burned for several days, destroying most of the site and emitting large clouds of black smoke into the atmosphere.

The affected tank was being filled by pipeline when it overflowed. Large quantities of petrol vapour were generated.

Tank levels were normally controlled from a control room using the automatic tank gauging (ATG) system. A servo level gauge measured the liquid level. The ATG system enabled the operator to monitor levels, temperatures and tank valve positions, and to initiate the remote operation of valves all from the control room on HSOL West site.

The tank also had an independent safety switch, which provided the operator with a visual and audible alarm in the control room when the level of liquid in the tank reached its specified maximum level (the 'ultimate' high level). This alarm also initiated a trip function to close valves on relevant incoming pipelines.

Examination of the records for Tank 912 from the ATG system suggests an anomaly. A little after 03.00 on 11 December 2005, the ATG system indicated that the level remained static at about two thirds full. This was below the level at which the ATG system would trigger alarms. Nevertheless, flow rate into the tank continued at between 550 m^3/hour and 890 m^3/hour.

At the time of the incident, automatic shutdown did not take place. Tank 912 would have been completely full at approximately 05.20, overflowing thereafter. This timing is entirely consistent

with CCTV evidence and eyewitness accounts reporting on a dense vapour cloud at various times between 05.38 and 06.00. The overflow of unleaded petrol would therefore have been in the order of over 300 tonnes by 06.00 (when the first explosions occurred).

Simulation of the ultimate high level tank alarms (from the relevant electrical substation on site) and tests on the annunciator panel and the link to BPA prove that they worked normally. Tests on the override switch found that it had no effect on the audible and visual alarms from the annunciator, but it did, when switched to override, inhibit the alarm/trip signals being sent to BPA.

Conclusion: Multiple EC&I failures were significant contributory factors to this accident. Although not fully resolved because of damage to the equipment, poor or inadequate maintenance must be a prime suspect.



Figure 27: Buncefield fire, 2005.

Texas City

Texas City refinery is located 40 miles from Houston in Texas, USA. 1600 people work at the refinery plus contractors. It is one of the largest refineries in the USA, processing 460,000 barrels of crude oil/day, around 3% of gasoline US supplies.

The Texas City refinery explosion on 23rd March 2005 is well-documented. Fifteen oil workers died in the 2005 explosion at BP's refinery in Texas City, Texas. At least 170 others were also injured in the blast.

Selected key issues which contributed to the accident are given below. These issues relate specifically to issues in this Guide.

1. There was no fail-safe shutdown system.
2. A faulty high-level alarm was not reported.
3. There was loss of process control.
4. There were inadequate KPIs monitoring process safety.
5. Modifications were completed without rigorous MoC.

References are given at the back of this Guide. See also

http://www.csb.gov/index.cfm?folder=video_archive&page=trouble for a CSB video about the accident.



Figure 28: Texas City refinery fire and explosion, 2005.

Ariane 5 Launch Failure

This launch was the first of ESA's new Ariane 5 rocket launcher, which was a much bigger launcher than its predecessor Ariane 4.

37 seconds after launch from French Guiana on 4th June 1996, both duty and back-up Inertial Reference Systems (IRS's) failed, which led to launcher disintegration.

The cause was a software fault in equipment which was unchanged from Ariane 4 but which was unsuitable for the changed flight trajectory of Ariane 5. There was inadequate analysis and simulation of the systems in Ariane 5.

There were 2 IRS's with identical hardware and software. One was active and one was on hot stand-by. Because the flight trajectory was different from Ariane 4, the active IRS declared a failure due to a software exception. The stand-by IRS failed for the same reason.

The affected software module performed alignment of the inertial platform before launch – it actually had no function after launch. The software exception was inappropriately handled, although the supplier was only following the specification.

See also http://www.youtube.com/watch?v=kYUrqdUyEpI&feature=related

Conclusions:

(ii) The accident was caused by a software specification error.

(iii) This was compounded by a failure to review the software thoroughly for a new application (changing from Ariane 4 to Ariane 5), i.e. MoC failure.

Multiple redundant systems with common software may be prone to common mode failures.



Figure 29: The Ariane 5 Launcher and the launch failure of June 1996.

Some other significant EC&I-related incidents

Some interesting EC&I-related failures and incidents are described in Table 18.

Items 1, 2 and 5 relate to software-caused faults:

- Item 1 is an example of a problem with a SIL-certified smart instrument. Unwanted embedded software can cause equipment failure even if it does not directly interfere with

operation of the equipment. Third party SIL certificates do not give any guarantee of equipment safety.

- Item 2 is an example of a high-integrity ASIC failure due to common-cause software error.
- Item 5 is a well-known example of the difficulties of using Windows in safety-related applications

Item 4 relates to the well-known problem of tin 'whiskers' which can cause shorts e.g. across relay contacts. This problem may be compounded by the European Unions' RoHS legislation which seeks to outlaw lead-based solders. (The favoured alternatives are tin-based.)

Table 18: Some other significant EC&I-related incidents.

Item	Description of issue	Detail
1	Smart paperless chart recorder	A paperless chart recorder (where all the data is stored electronically, with a display screen that looks like a chart recorder) was found to exhibit faults; mostly going to sleep or constant rebooting. Eventually the fault was traced to a submarine warfare game embedded in the software. (This sort of unwanted embedded software is usually called an 'Easter Egg'.) The game could cause memory overload and loss of data. The recorder had a third party SIL certificate.
2	Common-cause software error	In 1999 an incident at Uljin Nuclear Power Station Unit 3 in Korea corrupted data on the performance net of the plant control computer. The incident was caused by the failure of an Application-Specific Integrated Circuit (ASIC) chip on a rehostable module, which is part of a network interface module. Several non-operational pumps started without any demand, some closed valves opened and other open valves closed, and some circuit breakers switched on or off. There was also some relay chattering. Due to the response of the operators and because of diverse systems, the incident was mitigated without adverse consequences. A review of the systems found that a common-cause software error was the likely cause. It was found that there was no provision to protect against foreign writes in the global memories within the communication network. As a result, software modifications were implemented that included a change of data format, mirror testing, status testing, and hardware foreign write protection. Extensive modifications, including hard-wired backups, were subsequently carried out.

Item	Description of issue	Detail
3	IC failure due to electro migration	In 2001 a failure of control rod transponder circuit boards at Kashiwazaki-Kariwa Nuclear Power Station Unit 5 (Japan) rendered the control rods inoperable. Following detection of the defective cards, an analysis revealed that the failure mechanism was aluminium wire breakage in the ICs caused by electro migration (the transport of metal atoms induced by high electric current). Aluminium grain size was too small which increased susceptibility to electro migration. The affected ICs had been manufactured between 1985 and 1990. Failure analysis methods and manufacturing quality control and testing have been improved. This effect is potentially more significant in more modern ICs where the level of miniaturisation is much greater.
4	Tin whiskers/ EU RoHS Directive	Tin whiskers are extremely thin single crystal growths which can grow from tin or tin-alloy surfaces to lengths of over 20 millimetres. This can lead to shorting e.g. across relay contacts. This phenomenon in electronic components is well-documented. For example, see photos in http://nepp.nasa.gov/WHISKER/PHOTOS/INDEX.HTML However, this issue is likely to be exacerbated by the EU Restrictions of Hazardous Substances (RoHS) Directive 2006 which will greatly increase the use of lead-free solders. Lead-free solders are: generally tin-based, may require higher reflow temperatures, may require more active fluxes, are more brittle, and may be vulnerable to thermal cycling.

Item	Description of issue	Detail
5	Use of Windows in safety-related applications	USS Yorktown is a guided-missile cruiser and was the first to be outfitted with “Smart Ship” technology which used off-the-shelf PCs to automate tasks that sailors traditionally did themselves. This system was being tested when there was a widespread system failure off the coast of Cape Charles, Virginia in September 1997. After a crew member had mistakenly entered a zero into the data field of an application, the computer system proceeded to divide another quantity by that zero. The operation caused a buffer overflow, in which data leak from a temporary storage space in memory, and the error crashed the Windows NT system and brought down the ship’s propulsion system. The Yorktown was left “dead in the water” and had to be towed into the naval base at Norfolk, Va. http://www.sciamdigital.com/index.cfm?fa=Products.ViewIssuePreview&ISSUEID_CHAR=95C97E8D-4E3A-4EE5-A478-944FC3A850A&ARTICLEID_CHAR=F41481E3-A5CB-4267-B192-082E4C670D7

Appendix 4 Project Management Issues for Large EC&I Refurbishment Projects

Sound project management arrangements can go a long way to help mitigate the risks of IT project failure. This issue was addressed in some detail in the Royal Academy of Engineering/British Computer Society (RAE/BCS) report "*The Challenges of Complex IT Projects*" (2004) which is recommended. Some brief extracts are noted below:

"It cannot be guaranteed that following the guidance in this report will prevent project failure. However, there is a strong probability that ignoring it will prevent success."

"Various studies have examined common causes of failure in large IT projects. The National Audit Office (NAO) and Office of Government Commerce (OGC), for example, have compiled a list of the eight most common causes of failure in public sector IT projects, most of which seem equally applicable to the private sector:

1. Lack of clear link between the project and the organisation's key strategic priorities, including agreed measures of success.
2. Lack of clear senior management and Ministerial ownership and leadership.
3. Lack of effective engagement with stakeholders.
4. Lack of skills and proven approach to project management and risk management.
5. Lack of understanding of and contact with the supply industry at senior levels in the organisation.
6. Evaluation of proposals driven by initial price rather than long term value for money (especially securing delivery of business benefits).
7. Too little attention to breaking development and implementation into manageable steps.
8. Inadequate resources and skills to deliver the total portfolio."

"Customers should ensure that all senior IT practitioners involved in the design and delivery of high consequence systems have attained Chartered status……."

The RAE/BCS report also contains a succinct list of key issues for senior management for IT projects, most of which relates also to large EEC&I refurbishment projects on modern process plant. This list is given below. Of course 'normal' IT projects may not have safety functional requirements as well normal functional requirements; hence safety is an additional aspect of safety-related EEC&I projects involving Programmable Electronic Systems (PES). Nevertheless this list of key issues remains important.

Advice for Senior Management: Five Key Issues. [From RAE/BCS report "The Challenges of Complex IT Projects" (2004)]

1. The Project

Before embarking on any major IT project, ask yourself the following questions:

• *Why are we doing this?*
• *What contribution will this make, not just to a specific problem but to the overall business strategy?*
• *Am I, as the CEO/IT Director/Finance Director, prepared to devote enough time in my 80 hour week to the understanding of what this project is and to monitoring its progress?*
• *Are my expectations of this project, including time-scale and budget, realistic?*
• *Have we clearly and unambiguously recorded the ten most important requirements for this system?*
• *How important is it that we do this, given that it will cost a huge amount of money, time and disruption?*
• *Can we sustain this with all the other things that are going on as well?*
• *Am I confident that I have people with the right skills, and knowledge of IT and the application, who I can trust to handle this project?*
• *Have we done something like this before?*
• *Do we understand the risks involved with this project?*
• *What are we doing to manage those risks?*
• *How would this project be affected if the market changed, or a new technology became available?*
• *Do I have a recovery mechanism if everything goes wrong?*
• *Am I managing this organisation in a way that is conducive to project success?*

If you do not feel qualified to answer these questions, seek expert help. If necessary, employ an independent review team to assist in addressing these questions and monitoring progress.

2. The People

Ensure that three individuals, not committees, are publicly identified by name:

• The overall *executive sponsor* who will receive the glory for success or memorial for failure of the project;
• The *systems architect;*
• The *project manager.*

3. The Benefit

Make sure that your staff can clearly define the business benefit that will be delivered by the project – this must be absolutely comprehensible and defensible. If different key staff members give you different answers to this question, you have cause for concern. Also ensure that you know how delivery of the business benefit will ultimately be assessed, and who will take responsibility for that process.

4. The Complexity

It is generally less important that you understand how the benefit will be delivered, i.e. the details of the software. However, a general rule is ‘keep it simple’. This means avoiding big bang project implementations unless essential and being willing to use off the shelf packages where possible, adapting your business and management processes to fit the system rather than tailoring the system to suit your organisation. Although this may seem an unattractive compromise, the chances of achieving a successful outcome will be drastically improved.

5. The Progress

Finally, throughout the course of the project, ask your staff what worries them most about the project and what could go wrong. Their answers are likely to be much more informative than if you ask them whether everything is on track!

Appendix 5 Databases and Analysis Methodologies

Data Sources

Accident and incident data from three databases were examined.

1. RIDDOR (UK only): (Reporting of Injuries, Diseases and Dangerous Occurrences Regulations): Under RIDDOR there is a legal duty to report work-related deaths, major injuries or over-three-day injuries, work related diseases, and dangerous occurrences (near miss accidents). These reports are held on a HSE database and enables the Health and Safety Executive and local authorities to identify where and how risks arise, and to investigate serious accidents. A sub-set of the RIDDOR database has been provided containing a total of 3142 major, loss of containment accidents in the UK process industry. The period covered by this data is from 1996 to 2008. The initial filtering and formatting of the RIDDOR data to extract the loss of containment events was undertaken by HSE data specialists familiar with the RIDDOR and supporting databases.

2. MARS (Europe): The Major Accident Reporting System (MARS) was established to handle the information on 'major accidents' submitted by Member States of the European Union to the European Commission in accordance with the provisions of the 'Seveso Directive'. Currently, MARS holds data on more than 450 major accident events covering the period 1980 through to 2006. Information submitted to MARS may, where national provisions so require, be kept confidential if it calls into question, for example, the confidentiality of the deliberations of the Competent Authorities and the Commission, public security, personal data and/or files, commercial and industrial secrets, etc. However, without violating these aspects, access to the register and information system is open to government departments of the Member States, industry or trade associations, trade unions, non-governmental organisations in the field of the protection of the environment and other international or research organisations working in this field. The MARS data extract provided by the HSE for this project includes accident descriptions for 348 major accidents across Europe. It has a large number of data fields and sometimes written in poor English. Plant function is sometimes not clear.

3. MHIDAS (Worldwide): The Major Hazard Data Service (MHIDAS) is a database of incidents involving hazardous materials which had, or had the potential to have, an impact in terms of fatality, injury or damage to property or the natural environment. The database was formed circa 1985 from several other databases available at that time. The current version of the MHIDAS database contains over 16,000 records corresponding to over 14,000 incidents, and has been used to search for data to support the HSE Ageing Plant project. The database includes incidents which incurred casualties, required evacuation of either on-site or off-site personnel or caused damage to property or the natural environment, together with incidents which could, but for

mitigating circumstances, have led to the above occurring. Some particular types of incidents, such as those involving radioactive materials for example, are specifically excluded from the database. Incidents are not generally entered onto the database until a year after they have occurred so that as much information as possible can be collected for each incident from a number of different types of journals. MHIDAS is an AEA Technology-hosted database. Details of plant and its function can be limited since much of the information is drawn from press reports and insurance databases. An extract of the database containing 2951 process industry accidents was generated for this ageing plant review.

These databases were searched using an initial set of keywords intended to highlight incident reports where one of the contributing factors could potentially be ageing. Due to limitations of the keyword search approach, these were supplemented by manual reviews of the data to extract any relevant events.

A range of other previous HSE reports were also reviewed as part of the study:

- Loss of containment incident analysis (SPC/Enforcement/90)
- Loss of Containment Incident Analysis (HSL/2003/07)
- Findings from Voluntary Reporting of Loss of Containment Incidents 2005/06
- Findings from Voluntary Reporting of Loss of Containment Incidents 2004/05
- Investigation of loss of containment dangerous occurrences (SPC/Enforcement/132)

These previous HSE reports are discussed in Section 4.6 of the main report.

HSE Databases Data Extraction: RIDDOR

The HSE's own database experts conducted an internal filtering of RIDDOR data to extract those events (Dangerous Occurrences) that involved a loss of containment event. The extraction focussed on data from recent years as this was considered the most robust in terms of data fields and descriptive data searches. The filtering resulted in 3142 events being extracted for analysis covering dates from May 1996 to September 2008.

Consideration was also given to an analysis of the COIN database, which contains supplementary information. However, some tentative searches of this data produced few relevant records (~96) and there were issues with record duplication and the robustness of the data. As a result, this data was not used for the ageing analysis.

MHIDAS

The MHIDAS database is operated by AEA Technology on behalf of the HSE. The MHIDAS database manager, who has a very detailed knowledge of the data, undertook the initial data filtering and searches to extract data that may be of relevance to ageing plant and equipment. The initial filtering was to search for events involving a loss of containment from process plant and equipment.

In undertaking this data search, incidents coded as involving process plant were selected from the database. This resulted in an extraction of 2951 events. This data was taken forward for more detailed analysis. All these 2951 events were reviewed by the project team to identify ageing issues.

Additional searches were performed by the MHIDAS database team to highlight incidents coded as involving 'corrosion' or 'fatigue'. These are causation keywords for the MHIDAS database, and were also part of the suggested list of RIDDOR search keywords that was compiled for this project.

A number of text searches were then undertaken on these process related incidents, to give a feel for the data that could be available for this project. The first search simply looked for incidents where the word 'old' was mentioned in the abstract, in an appropriate context for this study. Further searches looked for words such as crack / cracks / cracked, vibration / vibrations and seize / seized / seizure in the abstract field, for the selected process incidents. These words were again part of the suggested list of RIDDOR search keywords that were compiled for this project.

MARS

A pre-filtered version of the MARS database was provided by HSE for the ageing plant analysis. This contained 348 records, and was based on those records made openly available from the MARS database. The incidents covered the period from 1980 through to 2006.

Ageing Specific Data Analyses

The RIDDOR, MHIDAS and MARS data extracted from the initial filtering process was subject to more detailed assessment to identify ageing related incidents for each topic area:

Primary Containment Systems
EC&I Systems
Management Systems
Structures
Safeguards

In general, the databases provided data that concentrated on the primary causes of the failures, which did allow the specific primary containment system failure mechanisms to be identified in many cases. Some difficulties arose where an incident was described as a ‘leak’ or ‘failure’ but without any description of the cause of the leak or failure. In some of these cases it was possible to deduce the nature of the failure from other information within the database, but if the cause could not be identified with a reasonably degree of confidence, then the event was not classified as an ageing event. Events were only classified as possibly ageing related where a clear ageing mechanism (e.g. corrosion) was identified or where the description context of the incident strongly indicated that ageing was one of the factors in the incident (e.g. the plant was in a poor condition).

Extracting useful data on the other topic areas was more difficult. The limited text field data in MHIDAS and RIDDOR made it very difficult to identify the role of management systems, structures or safeguards in the incidents, but a number of useful anecdotes could be extracted.

The data was considered insufficiently detailed or consistently recorded to allow any general analysis of the extent to which ageing related failures were present relating to these topic areas. Several EC&I failures were reported, but it was difficult to determine which of these may have been ageing related.

The MARS data was the most useful from an analysis point of view as it related to major accident events of direct relevance to the process industries, and because it contained several useful text fields giving a reasonable insight into the incidents and their effects.

The data analysis approach and results are summarised below for each topic area. The search keywords were developed by the topic specialists leading the various analyses.

Containment Systems

The following keywords were applied to the databases.

Containment System Keywords

Erosion
Corrosion
Stress
Fatigue
Mechanical Failure
Crack
Cracking
Collapse
Wear
Worn out
Old
Aged
Modification
loss of containment
LOC
structural failure
stress corrosion
corrosion under insulation
corrosion under lagging
lagging
insulation
CUI
degradation
deterioration
leak
seizure
vibration

The keyword search results were then further analysed manually.

This resulted in the following numbers of events being identified as potentially age related:

MHIDAS – 145 events were considered to be potentially age related containment failures. The MHIDAS data provided limited text information on the accidents and although keyword searches were attempted, it was decided that a line by line manual search of the fields was the only effective way to seek out relevant events.

MARS – 51 events were considered to be potentially age related containment failures. The MARS data provided several useful text fields on the accidents and although keyword searches were attempted, it was decided that a line by line manual search of all the data fields was the most effective way to seek out relevant events.

RIDDOR – An initial keyword search was conducted which extracted 342 records. These were reviewed manually and this identified 179 events as potentially age related containment failures.

EC&I Systems

The following keywords were applied to the databases.

EC&I System Keywords

Modification
Instrumentation Failure
C&I failure
I&C failure
Software
electrical failure
sensor
Old
Aged *
Instrument
Control

* the keyword ‘aged’ had to be used carefully since this text string brings up a wide variety of common words

The keyword search results were then further analysed manually.

This resulted in the following numbers of events being identified as potentially age related:

MHIDAS – 59 EC&I events were identified but the limited data meant that it was not possible to identify which of these may have been age related EC&I failures. The MHIDAS data provided limited text information on the accidents and although keyword searches were attempted (244 records extracted), it was decided that a line by line manual search of the fields was the only effective way to seek out relevant events.

MARS – 34 events were identified as being EC&I related and of these 21 were considered to be potentially age related EC&I failures. The MARS data provided several useful text fields on the accidents and although keyword searches were attempted (these identified 208 incidents), it

seek out relevant events.

RIDDOR – An initial keyword search was conducted which extracted 282 records. These were reviewed manually and this identified 36 events as being EC&I related and of these 12 events as potentially age related EC&I failures.

Management Systems

The following keywords were applied to the databases.

Management System Keywords

QA
QC
Management of Change
Modification
Competency
Integrity Management
HSE Procedure
loss of containment
LOC
degradation
deterioration
Risk Assessment
Hazard identification
Inspection
Audit
Review
Continuity
Interface
Knowledge Transfer
Resources
Records
Schedules
Action tracking
Responsibility
Authorities
KPI/KPTs
Incident Reporting
Documentation
Communications
Contractor Management

The keyword search results were then further analysed manually.

This resulted in the following numbers of events being identified as potentially age related:

MHIDAS – of the 722 events extracted by the keywords, 37 events were considered to be management system related. The data is insufficiently detailed to determine which if any of these were ageing related.

MARS – of the 191 events extracted by the keywords, 47 were considered to be management system related and only 1 event of these was considered to be specifically ageing related.

RIDDOR – An initial keyword search was conducted and the data extracts reviewed. This review of the text fields in this database revealed that little, if any, information was available on the specific role of management systems in the events. Further analysis was not considered worthwhile.

Structures

The following keywords were applied to the databases.

Structures Keywords

civil
bund
wall
building
embankment
subsidence
collapse
flood
tower
paving
gulley
culvert
concrete
brick

The keyword search results were then further analysed manually.

This resulted in the following numbers of events being identified as potentially age related:

MHIDAS – only 3 events were considered to be potentially age related structural failures. The MHIDAS data provided very limited text information on the accidents and although keyword searches were attempted, it was decided that a line by line manual search of the fields was the only effective way to seek out relevant events.

MARS – only 7 events were considered to be potentially age related structural failures. The MARS data provided several useful text fields on the accidents and although keyword searches were attempted, it was decided that a line by line manual search of all the data fields was the most effective way to seek out relevant events.

RIDDOR – An initial keyword search was conducted which extracted 129 records. These were reviewed manually and this identified 3 events as potentially age related structural failures.

Safeguards

The following keywords were applied to the databases.

Safeguards Keywords

bund
fire
safety
shutdown
ESD
pressure
fight
collapse
alarm
siren
spray
water
trip
isolate
drain
blast
wall
spill
disc
burst
safeguard
mitigat
rosov

The keyword search results were then further analysed manually.

This resulted in the following numbers of events being identified as potentially age related:

MHIDAS – only 11 events were considered to be potentially age related safeguards failures. The MHIDAS data provided very limited text information on the accidents and although keyword searches were attempted, it was decided that a line by line manual search of the fields was the only effective way to seek out relevant events.

MARS – only 15 events were considered to be potentially age related safeguards failures. The MARS data provided several useful text fields on the accidents and although keyword searches were attempted, it was decided that a line by line manual search of all the data fields was the most effective way to seek out relevant events.

RIDDOR – An initial keyword search was conducted which extracted 527 records. These were reviewed manually and this identified 13 events as potentially age related safeguards failures.

A summary of the events classified as ‘ageing’ related in the MARS database are presented below:

Table 19: MARS Data Ageing Analysis by Category.

MARS Database Accident Code	Corrosion	Fatigue	Wear	HSEMS	Safeguards	Structural	C&I	All Ageing	Double Count?
**/1998/001-[01]									
**/2002/001-[01]									
**/1986/003-[01]									
**/1987/001-[01]									
**/1988/001-[01]	1							1	
**/1989/001-[01]		1						1	
**/1992/001-[01]	1							1	
**/1994/001-[01]									
**/1995/001-[01]									
**/1995/002-[01]									
**/1995/003-[01]									
**/1997/001-[01]	1							1	
**/1998/001-[01]									
**/1999/001-[02]									
**/1999/002-[01]	1							1	
**/2000/001-[01]									
**/2002/001-[01]									
**/2002/010-[01]									
**/2005/002-[01]									
**/2005/004-[01]									
**/2000/001-[01]									
**/2002/004-[04]									
**/2003/001-[01]									
**/2006/001-[01]							1	1	
**/1980/001-[01]	1							1	
**/1981/001-[01]									
**/1981/003-[01]	1							1	
**/1983/002-[01]	1							1	
**/1983/003-[01]					1			1	
**/1984/001-[01]	1							1	
**/1984/002-[01]						1	1	1	2
**/1984/003-[01]					1			1	
**/1984/004-[01]									
**/1985/001-[01]									
**/1985/002-[01]									

MARS Database Accident Code	Corrosion	Fatigue	Wear	HSEMS	Safeguards	Structural	C&I	All Ageing	Double Count?
**/1986/002-[01]									
**/1987/001-[01]									
**/1987/002-[01]									
**/1988/001-[01]					1			1	
**/1988/002-[01]									
**/1988/004-[01]									
**/1988/005-[01]	1							1	
**/1989/003-[01]									
**/1989/005-[01]									
**/1990/001-[01]									
**/1990/003-[01]									
**/1990/004-[01]									
**/1991/001-[01]	1							1	
**/1991/002-[01]									
**/1991/004-[01]	1				1			1	2
**/1991/005-[01]	1							1	
**/1991/006-[01]									
**/1991/007-[01]							1	1	
**/1991/009-[01]									
**/1991/011-[01]									
**/1991/012-[01]	1							1	
**/1991/013-[01]									
**/1992/006-[01]									
**/1993/001-[01]									
**/1993/002-[01]			1					1	
**/1993/004-[01]									
**/1993/005-[01]									
**/1993/007-[01]									
**/1993/008-[01]							1	1	
**/1993/016-[01]									
**/1994/001-[01]									
**/1994/002-[01]									
**/1995/002-[01]									
**/1995/003-[01]									
**/1995/004-[01]									
**/1996/006-[01]									
**/1996/008-[01]									
**/1997/003-[01]	1							1	
**/1997/008-[01]									
**/1997/010-[01]									
**/1997/011-[01]	1							1	

MARS Database Accident Code	Corrosion	Fatigue	Wear	HSEMS	Safeguards	Structural	C&I	All Ageing	Double Count?
**/1998/002-[02]	1							1	
**/1998/003-[02]									
**/1998/004-[02]									
**/1998/005-[02]									
**/1998/007-[02]									
**/1998/008-[02]									
**/1998/009-[02]	1							1	
**/1998/010-[02]									
**/1998/014-[02]									
**/1998/015-[02]	1							1	
**/1999/004-[01]									
**/1999/005-[01]									
**/1999/006-[01]									
**/1999/007-[01]									
**/1999/010-[01]							1	1	
**/2000/001-[01]						1		1	
**/2000/003-[01]									
**/2000/005-[01]									
**/2000/006-[01]									
**/2000/007-[01]									
**/2001/005-[01]									
**/2001/024-[01]									
**/2002/005-[01]									
**/2003/004-[01]									
**/2005/003-[01]	1							1	
**/2005/005-[01]									
**/1980/001-[01]									
**/1986/001-[01]									
**/1987/001-[01]									
**/1990/002-[01]									
**/1996/001-[01]									
**/2002/001-[01]									
**/1988/002-[01]									
**/1989/001-[01]									
**/1990/003-[01]							1	1	
**/1991/001-[01]									
**/1991/002-[01]									
**/1992/001-[01]						1		1	
**/1992/002-[01]									
**/1993/001-[01]									
**/1993/002-[01]					1			1	

MARS Database Accident Code	Corrosion	Fatigue	Wear	HSEMS	Safeguards	Structural	C&I	All Ageing	Double Count?
**/1996/001-[01]	1							1	
**/1996/002-[01]									
**/1996/003-[01]					1			1	
**/1996/004-[01]									
**/1999/002-[01]	1					1		1	2
**/1999/003-[01]									
**/2002/001-[01]	1							1	
**/2003/001-[01]									
**/2004/001-[01]									
**/2005/001-[01]									
**/1997/001-[01]									
**/1997/002-[01]									
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**/2001/001-[01]	1							1	
**/2003/001-[01]							1	1	
**/1986/003-[01]									
**/1987/001-[01]									
**/1989/002-[01]									
**/1990/001-[01]	1							1	
**/1991/001-[01]									
**/1992/001-[01]									
**/1992/002-[01]									
**/1993/001-[01]									
**/1993/002-[01]									
**/1994/002-[01]									
**/1994/003-[01]									
**/1994/006-[01]									
**/1994/008-[01]									
**/1994/010-[01]									
**/1994/011-[01]							1	1	
**/1994/013-[01]									
**/1994/014-[01]									
**/1994/015-[01]							1	1	
**/1995/001-[01]									
**/1995/004-[01]									
**/1995/005-[01]									
**/1995/006-[01]									
**/1995/008-[01]									
**/1996/001-[01]	1							1	
**/1996/002-[01]									
**/1996/004-[01]									

MARS Database Accident Code	Corrosion	Fatigue	Wear	HSEMS	Safeguards	Structural	C&I	All Ageing	Double Count?
**/1996/005-[01]									
**/1996/009-[01]									
**/1996/011-[01]									
**/1997/003-[01]									
**/1997/004-[01]									
**/1997/005-[01]									
**/1997/012-[02]									
**/1998/002-[01]									
**/1998/004-[01]						1		1	
**/1998/005-[01]						1	1	1	2
**/1998/006-[01]						1		1	
**/1998/008-[01]									
**/1998/009-[01]									
**/1998/014-[01]									
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**/1998/017-[01]		1						1	
**/1998/020-[01]			1					1	
**/1998/021-[01]									
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**/2000/001-[01]							1	1	
**/2000/002-[01]									
**/2000/003-[01]									
**/2000/004-[01]									
**/2000/005-[01]									
**/2000/006-[01]									
**/2001/001-[01]									
**/2001/003-[01]									
**/2001/006-[01]									
**/2001/007-[01]	1							1	
**/2001/008-[01]									
**/2001/009-[01]									
**/2002/001-[01]									
**/2002/002-[02]									
**/2002/005-[02]	1							1	
**/2002/006-[02]									
**/2003/002-[02]									
**/2003/008-[02]									
**/2004/001-[02]									

MARS Database Accident Code	Corrosion	Fatigue	Wear	HSEMS	Safeguards	Structural	C&I	All Ageing	Double Count?
**/2004/003-[02]									
**/2004/006-[02]	1							1	
**/2005/001-[01]					1			1	
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**/1986/001-[01]									
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**/1994/006-[01]									
**/1994/008-[01]									
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**/1996/002-[01]									
**/1997/001-[01]					1			1	

MARS Database Accident Code	Corrosion	Fatigue	Wear	HSEMS	Safeguards	Structural	C&I	All Ageing	Double Count?
**/1997/005-[01]									
**/1997/006-[01]	1							1	
**/1997/007-[01]							1	1	
**/1998/001-[01]									
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**/1999/013-[01]	1							1	
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**/2000/002-[02]				1				1	
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**/1988/004-[01]			1					1	
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**/1985/002-[01]	1							1	
**/1985/003-[01]									
**/1987/001-[01]									
**/1988/002-[01]									

MARS Database Accident Code	Corrosion	Fatigue	Wear	HSEMS	Safeguards	Structural	C&I	All Ageing	Double Count?
**/1988/003-[01]									
**/1988/004-[01]									
**/1991/001-[01]									
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**/1996/001-[01]									
**/1996/003-[01]									
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**/1991/001-[01]							1	1	
**/1991/002-[01]									
**/1995/001-[01]									
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**/1998/001-[03]									
**/1999/001-[01]	1							1	
**/2000/003-[01]									
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**/2002/005-[01]	1							1	
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**/2003/004-[01]									
**/2003/006-[01]									
**/2003/009-[01]									
**/2004/001-[01]									

MARS Database Accident Code	Corrosion	Fatigue	Wear	HSEMS	Safeguards	Structural	C&I	All Ageing	Double Count?
**/2004/002-[01]									
**/2004/003-[01]	1							1	
**/2004/004-[01]									
**/2005/002-[01]									
**/2005/003-[01]	1							1	
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**/2000/001-[03]									
**/2000/002-[01]									
**/2004/001-[01]									
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**/2005/001-[01]		1						1	
**/2005/002-[01]									
**/2000/003-[01]									
**/2000/004-[01]									
**/2001/003-[01]									
**/2001/005-[01]									
**/2003/001-[01]									
**/1985/001-[01]									
**/1994/001-[01]		1						1	
TOTALS	45	8	4	1	15	7	21	96	5

Note: the categories corrosion, fatigue and wear are all considered ageing related failures and apply to the containment systems.

The double counting field indicates where an incident has been classified in more than one ageing failure category.

The country codes in the data record identifiers have been anonymised.

HSE

Health and Safety Executive

Managing Ageing Plant

A Summary Guide

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The potential degradation of plant and equipment due to age related mechanisms such as corrosion, erosion and fatigue is a key issue for industry. The Health and Safety Executive have recognised asset integrity management and the issue of ageing plant as key topics to address in their inspection programmes.

The Health and Safety Executive has conducted research into these aspects for offshore oil and gas installations and has now conducted work to extend this in the context of hazardous onshore COMAH facilities in particular. As part of this ongoing work, the Health and Safety Executive has been developing internal processes and priorities for these key areas, supported by technical documents to raise awareness and understanding of the issues.

In line with the Health and Safety Executive's role to disseminate information and awareness, these supporting documents are being made available to industry to assist them when addressing ageing plant.

This report, being published to augment the existing RR509[1], provides an overview of ageing plant mechanisms and their management and presents the findings of an analysis of loss of containment events to indicate the extent to which ageing plant mechanisms are a factor.

We hope this document will provide industry with a good understanding of the Health and Safety Executive's views and concerns on this important topic, and provide a useful basis for engagement with industry to ensure the continued safe operation of plant and equipment over many years.

This report and the work it describes were funded by the Health and Safety Executive (HSE). Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.

HSE Books

FOREWORD

The potential degradation of plant and equipment due to age related mechanisms such as corrosion, erosion and fatigue is a key issue for industry. The Health & Safety Executive have recognised asset integrity management and the issue of ageing plant as key topics to address in their inspection programmes.

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Yours,

Health & Safety Executive

Executive Summary

The issue of ageing plant, leading to an increased risk of loss of containment and other failures due to plant and equipment deterioration, has been shown to be an important factor in incidents and accidents.

Recent research shows that 50% of European major hazard 'loss of containment' events arising from technical plant failures were primarily due to ageing plant mechanisms such as erosion, corrosion and fatigue. This data analysis for HSE (Ageing Plant Study Phase 1 report [2]) has shown that across Europe, between 1980 and 2006, there have been 96 major accident potential loss of containment incidents reported in the EU Major Accident Database (MARS) which are estimated to be primarily caused due to ageing plant mechanisms. This represents 30% of all reported 'major accident' loss of containment events in the MARS database, and 50% of the technical integrity and control and instrumentation related events. These 'ageing' events equate to an overall loss of 11 lives, 183 injuries and over 170Million € of economic loss. This demonstrates the significant extent and impact of ageing plant related failures on safety and business performance.

This finding is supported by RIDDOR data which has shown that between 1996 and 2008 it is estimated that there have been 173 loss of containment incidents reported in RIDDOR that can be attributed to ageing plant mechanisms. The short timescales required to send the RIDDOR incident reports to HSE before proper investigation of the root causes can sometimes be completed means that it can be difficult to identify which events may be ageing related: so the actual number could be much higher than that quoted here.

This Technical Resource document has been prepared to assist managers at onshore hazardous COMAH facilities and HSE inspectors in this key topic area.

The guide provides:

- Background information on the topic of ageing plant including a definition of ageing plant, and an analysis of accident data to show its extent and implications
- A summary of the key ageing mechanisms, including their signs and symptoms, the type of plant and process most susceptible to these mechanisms and current good practice for managing these
- Information on where to obtain more detailed information and advice

It is hoped that the guide will also provide a useful resource for industry, both in terms of understanding HSE's approach, understanding the issues and expectations on industry for managing ageing assets, and in raising awareness throughout industry of the effects of ageing plant and how this can be managed effectively.

Contents

1.0 INTRODUCTION 1

1.1 Purpose 1

1.2 Scope 1

1.3 Definition of Ageing Plant 1

1.4 Ageing Asset Types 2

1.5 Prevalence and Impact of Ageing on Major Hazard Plant 4

2.0 AGEING MECHANISMS AND THEIR MANAGEMENT 6

2.1 Ageing Mechanisms and What they can Affect 6

2.2 Corrosion 8

2.2.1 Mechanisms 8

2.2.2 Signs and Symptoms 13

2.2.3 Susceptibility 13

2.2.4 Management Options 14

2.3 Stress Corrosion Cracking 14

2.3.1 Mechanisms 14

2.3.2 Signs and Symptoms 15

2.3.3 Susceptibility 15

2.3.4 Management Options 17

2.4 Erosion 17

2.4.1 Mechanisms 17

2.4.2 Signs and Symptoms 17

2.4.3 Susceptibility 17

2.4.4 Management Options 18

2.5 Other mechanisms 18

2.6 Some Key Specific Issues 18

2.6.1 Corrosion Under Insulation (CUI) 18

2.6.2 Machines & Rotating Equipment 20

2.6.3 Fired Heating Equipment 21

2.6.4 Non-Metallic Materials 21

2.6.5 Concrete Support Structures 22

2.6.6 Glass Reinforced Plastic (GRP)/Glass Reinforced Epoxy (GRE) Tanks 23

2.6.7 Buried Pipes 24

3.0 MANAGEMENT OF AGEING 25

4.0 EC&I SPECIFIC GUIDANCE 29

4.1 Introduction 29
4.1.1 What is “Ageing E/C&I equipment”? 30
4.1.2 Significance of E/C&I Equipment Lifetimes 31
4.1.3 Issues related to Ageing E/C&I Equipment in incidents 31
4.2 E/C&I Maintenance Management 33
4.2.1 Maintenance Planning 33
4.2.2 Procurement – Spares and Support Issues 34
4.2.3 Plant History and Other Experience 34
4.2.4 KPIs for Management of E/C&I Ageing 35
4.3 E/C&I Management of Change 37
4.3.1 Management of Change (MoC) Capability 37
4.3.2 Software Maintenance and Configuration Management of Plant Computer Control Systems 37
4.3.3 Project Management Issues for Large E/C&I Refurbishment Projects 38

5.0 WHERE TO FIND OUT MORE 39
5.1 Accident statistics and analysis 39
5.2 Ageing mechanisms and their management 39
5.3 Good practice guides 39

REFERENCES 40

Acronyms and Abbreviations

AIMS	Asset Integrity Management System
BA	Breathing Apparatus
CCTV	Closed Circuit Television
COMAH	The Control of Major Accident Hazard Regulations 1999
CP	Cathodic Protection
CRA	Corrosion Resistant Alloy
CUI	Corrosion Under Insulation
DCS	Distributed Control System
E/C&I	Electrical, Control and Instrumentation
ER	Electrical Resistance (Probe)
ESD	Emergency Shutdown System
GRE	Glass Reinforced Epoxy
GRP	Glass Reinforced Plastic
HIC	Hydrogen Induced Cracking
HSE	The Health and Safety Executive
HSEMS	Health, Safety and Environment Management System
HV	High Voltage
HVAC	Heating, Ventilation and Air Conditioning
KPI	Key Performance Indicator
LoC	Loss of Containment
LPR	Linear Polarisation Resistance (Probe)
MARS	European Union Major Hazards Incident Database
MHIDAS	World-wide major hazard incident database
MIT	Maintenance, Inspection and Test
MoC	Management of Change
NDT	Non Destructive Testing
OEM	Original Equipment Manufacturer
PA	Public Address (System)
PLC	Programmable Logic Controller
PPE	Personal Protective Equipment
RBI	Risk Based Inspection
RIDDOR	Reporting of Injuries, Diseases and Dangerous Occurrences Regulations 1995
SCADA	Supervisory Control and Data Acquisition System
SCC	Stress Corrosion Cracking
SCE	Safety Critical Element
SRB	Sulphate Reducing Bacteria
UPS	Uninterruptible Power Supply

1.0 Introduction

1.1 Purpose

The purpose of this guide is to provide targeted information to help HSE inspectors better understand the issues of ageing plant and to promote good practice for managing ageing assets.

It is hoped that the guide will also provide a useful resource for industry, both in terms of understanding HSE's approach, understanding of the issues and expectations on industry for managing ageing assets, and in raising awareness throughout industry of the effects of ageing plant and how this can be managed effectively.

1.2 Scope

This guidance is particularly relevant to the topic of ageing plant in refineries, other hydrocarbon processing plant, chemical process plant and storage facilities, and other similar establishments onshore, and also has relevance to offshore oil and gas installations.

Although this guide is primarily targeted at the process and chemicals sector, many of the ageing issues are also generic to any form of containment or structural feature, or instrumented protective system and so aspects of the guide may also be of use more widely within industry.

1.3 Definition of Ageing Plant

The term 'ageing plant' can be misleading, it is not just related to the age and design life of a plant, system, or piece of equipment. Previous work for the HSE (Research Report 509 on Ageing Plant) [1] defined ageing and ageing plant as:

"Ageing is not about how old your equipment is; it is about its condition, and how that is changing over time. Ageing is 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 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."

Overall, ageing plant is plant which is, or may be, no longer considered fully fit for purpose due to deterioration or obsolescence in its integrity or functional performance. 'Ageing' is not directly related to chronological age. There are many examples of very old plant remaining fully fit for purpose, and of recent plant showing evidence of accelerated or early ageing, e.g. due to corrosion, fatigue or erosion failures.

1.4 Ageing Asset Types

It is important to recognise that many systems and features which may be subject to ageing, can contribute to the health, safety and environmental performance of plant, or could compromise the performance were they to fail or collapse. A broad view is therefore required when assessing the potential impact of ageing at a given installation.

The various asset types can be segregated into four basic categories:

- Primary containment systems
- Control & Mitigation Measures, i.e. Safeguards
- EC&I systems
- Structures

EC&I systems can be considered as a type of safeguard. However, given the different nature and relative importance of the functions performed by this type of equipment, it is considered desirable to highlight this category specifically.

Table 1 sets out the types of physical assets or features that may be subject to ageing.

Table 1: Physical Assets Considered Relevant to Ageing

Asset Type	Examples
Primary Containment Systems (Process and Utilities)	Static Elements – vessels, pipework and fittings, whether at significant pressure or not, e.g. pressure vessels, columns, heat exchangers, storage tanks, open top tanks, pipework, and pipework fittings such as valves, strainers, flanges, ejectors, etc
	Rotating / Motive Elements, e.g. pumps, compressors, turbines, agitators, fans, solids handling equipment, etc
Control & Mitigation Measures	Process Safeguard Systems, e.g. • Mechanical pressure protective systems - pressure/ vacuum relief valves, bursting discs, vents and flares • Mechanical overfilling protective systems - overflows, emergency dump systems • Ignition source control equipment, eg earthing, equipment enclosures, etc • Inerting systems (e.g. nitrogen blanketing and purging) • Trace heating, cooling or other thermal insulation systems for process insulation or operator protection
	Secondary or Tertiary Containment Systems, e.g. • Double skin vessels and pipes • Bunds • Paved areas, kerbing, gulleys, sumps, etc • Under soil/ underground non-permeable membranes and land drains • Drainage systems • Effluent treatment systems, interceptors, penstock valves for

Asset Type	Examples
	outfall isolation, etc • Emergency holding tanks and lagoons, etc
Control & Mitigation Measures (continued)	Control and Mitigation Systems, e.g. • Action fire protection and firewater systems, including fusible loops or plugs, fire pumps, fire water lagoons or storage tanks, ring mains, hydrants, monitors, spray and deluge systems, etc • Passive fire protection systems • Blast protection, relief and suppression systems • Inert gas fire suppression systems (e.g. CO_2) • Impact protection systems e.g. crash barriers, dropped object protection, shielding • Gas knockdown or inerting systems • HVAC systems to prevent smoke or gas ingress or protect people or key safety critical equipment • Communication systems - telephones, radios, PA systems • Emergency lighting • Spill kits, and environmental spill / release clean up or control equipment and systems • Portable flammable gas and toxic gas monitors etc • PPE for use in an emergency - BA sets, gloves, chemical suits, face masks, etc • Rescue equipment • Emergency showers and eye wash stations • Portable fire extinguishers and manual fire fighting equipment
	External Hazard/ Environmental Safeguards, e.g. • Flood protection arrangements • Lightning protection • Trees or other natural features/ ecosystems that could impact plant/pipelines if they collapsed or caused root damage or burrowing, or block outfalls or overflows • Areas prone to subsidence, rock fall or land slip, etc
EC&I Systems	EC&I - safety critical process safeguarding systems (trips, alarms, process ESD, etc)
	EC&I - safety critical leak detection and response systems (fire and gas leak / area detection, emergency shutdown systems)
	Integrity and availability of key services such as power supply, UPS, emergency back up generators, battery units, etc
	CCTV Monitoring of plant areas and escape routes, etc
Structures	Supporting structures, civils features and foundations for: • Primary containment • Secondary and tertiary containment, including bunds, kerbs, drains, effluent and storm/ fire-water lagoons and basins • Providing impact protection, e.g. protection from vehicle collision, blast, lifting operations, gas cylinders, etc • Safe places of work, e.g. controls rooms, offices, workshops, emergency shelters • Access and escape routes, e.g. roadways, ladders, stairs, gantries, walkways, etc • Safety critical services and utilities, e.g. power distribution, equipment and battery rooms, etc

Asset Type	Examples
	Safety critical EC&I equipment, weatherproofing, ingress protection, etc Structures and civils features that could impact major hazard plant, pipelines or equipment (including EC&I and safeguarding equipment, cabling, etc) were they to collapse / fail, or which could disperse spilt material if they were to leak/ fail, e.g. flood defences, chimneys, communication towers, canal or reservoir embankment, sea defences, buildings, walls, flares/ stacks, tall lighting towers, earth embankments, retaining walls, culverts, bridges, tunnels, underground caverns, etc.

1.5 Prevalence and Impact of Ageing on Major Hazard Plant

Onshore chemical plant in the UK is ageing. Health and Safety Executive (HSE) field inspectors often have to consider the Operators' safety justification for continued use of ageing plant taking account of a variety of issues such as usage, design life, known research, known operational and failure history, maintenance and inspection history, etc. The issues also need to be considered against a background of increasing competition from overseas, and the pressure on resources and investment which this has had over recent years, with reductions in manning levels, retirement of experienced staff, and pressure on operating budgets.

From a health, safety and environmental perspective, there is a need to be able to identify those sites and installations where ageing may present a significant increase in risk. This will depend on several factors, including:

- The inherent hazards and risks of the installation
- The propensity of the installation to ageing related deterioration or damage
- The likely types of ageing mechanisms and where and how these could present themselves
- The extent to which ageing is being effectively managed

Recent research undertaken for HSE [2] addressed this by conducting a detailed review of available incident data to firstly ascertain if ageing is a significant issue and secondly to identify key factors or issues driving this.

The key databases interrogated were RIDDOR, including the chemical and process industry voluntary incident reporting schemes, MARS (EU Seveso II major hazard Incidents) and MHIDAS (Worldwide major hazard accidents).

The study found that, in terms of major accidental potential events at major hazard installations, the MARS data provides the most appropriate basis to assess the significance of ageing as these events should be directly applicable to UK COMAH installations or other chemical plant when considering major leaks and incidents. The study determined that the MARS data indicates that approximately **60% of major hazard loss of containment incidents are related to technical integrity and, of those, 50% have ageing as a contributory factor**. It therefore concluded that plant ageing mechanisms are a significant issue in terms of major hazard accidents.

The importance of ageing mechanisms is supported by RIDDOR data which has shown that between 1996 and 2008 it is estimated that there have been 173 loss of containment

incidents reported in RIDDOR that can be attributed to ageing plant mechanisms. The short timescales required to send the RIDDOR incident reports to HSE before proper investigation of the root causes can sometimes be completed means that it can be difficult to identify which events may be ageing related: so the actual number could be much higher than that quoted here. The limited details from the MHIDAS database also made it difficult to positively identify the role of ageing mechanisms, though it is considered likely that these mechanisms were involved in many incidents.

A significant observation from the data review was that positive identification of incident causes, especially related to plant ageing, can be difficult from the text descriptions provided in many accident databases. There is significant variation in the degree of detail provided in the reports which limits the usefulness of the data in this kind of analysis. Experience from the review suggests that a useful development in RIDDOR reporting of incidents would be to include a simple checklist focused on causation, i.e. recording of contributing factors that emerge from the incident investigation.

Details of the analysis that led to the above observations can be found in the Phase 1 Report for this study [2].

2.0 Ageing Mechanisms and their Management

2.1 Ageing Mechanisms and What they can Affect

This section of the guide provides a brief introduction to the mechanisms that can lead to age related deterioration of plant, processes and equipment. It is intended to provide concise and focussed information for non-specialists who are involved with the management of ageing plant and HSE Regulatory Inspectors who may inspect ageing plant at onshore COMAH facilities to help them understand the key issues and know what key indicators to look for.

In cases where an inspection raises potential issues that require more specialist assessment or advice, then the relevant topic specialist expertise should be consulted.

The resources listed in Section 5.0 can be accessed if more a detailed understanding of the mechanisms is desired.

Various generic ageing mechanisms can be present depending on the circumstances. These can affect a variety of asset types. A summary of the ageing mechanisms and the asset types they can affect is presented in Table 2.

Table 2: Ageing Mechanisms Affecting Physical Assets

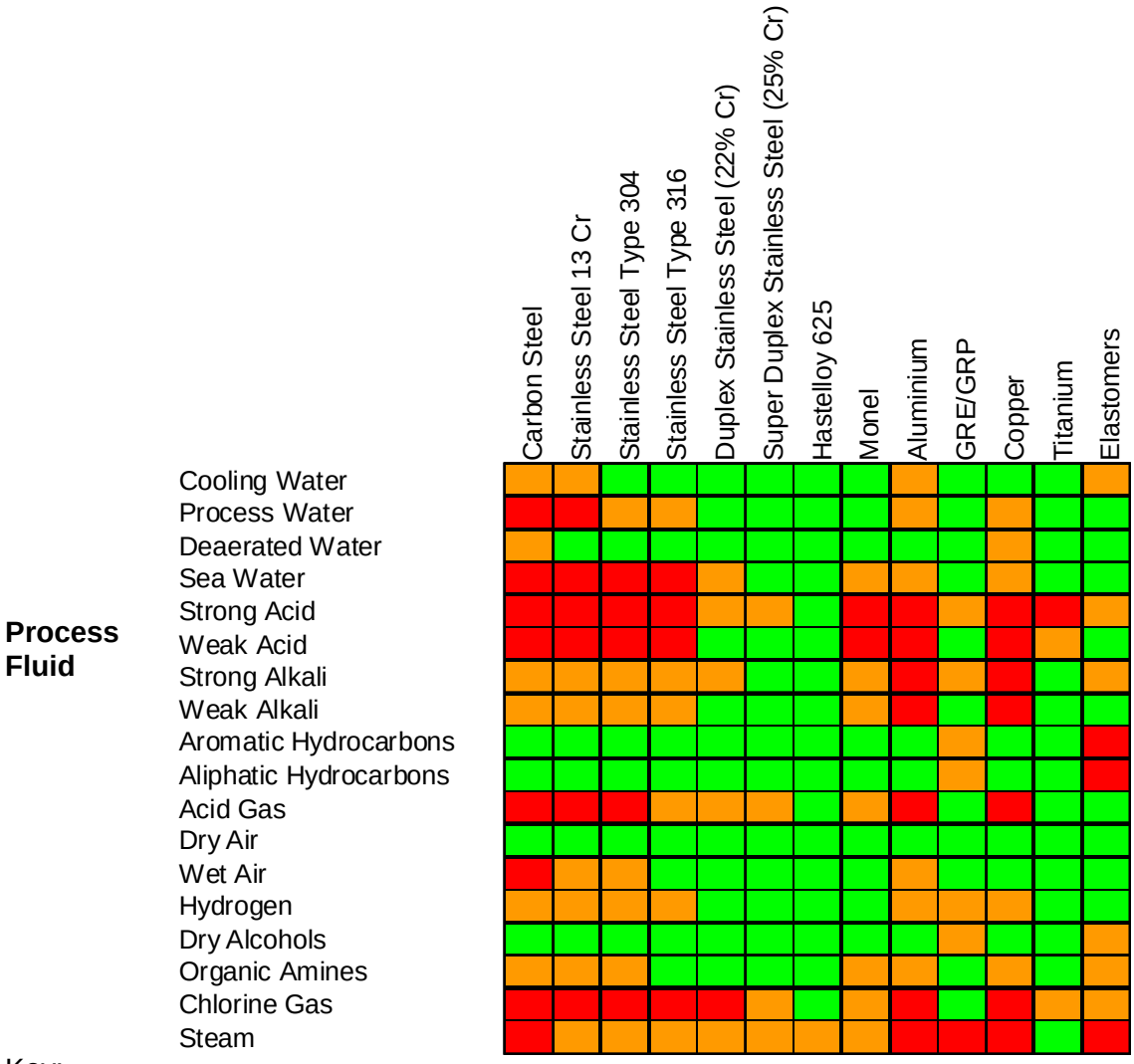
Ageing Mechanism	Primary Containment	Structures	Safeguards	EC&I
Corrosion	✓	✓	✓	✓
Stress Corrosion Cracking	✓	✓	✓	
Erosion	✓	✓	✓	✓
Fatigue	✓	✓	✓	
Embrittlement	✓	✓		✓
Physical damage	✓	✓	✓	✓
Spalling		✓		
Weathering		✓	✓	
Expansion/ contraction due to temperature changes (process or ambient) or freezing	✓	✓	✓	✓
Instrument drift				✓
Dry joint development				✓
Detector poisoning				✓
Subsidence		✓	✓	

In terms of primary containment a general list of damage types and mechanisms for pressurised equipment can be found in HSE RR509 [1].

Ageing degradation would be expected to be more prevalent where there is some degree of incompatibility between the process fluids and the materials of construction of the equipment. Table 3 provides an indicative guide to identifying which equipment on a plant may be more likely to be affected by ageing degradation, mainly drawing on material compatibility data.

Table 3: Indicative Guide to Ageing Plant Degradation

Material Type



Key:

High Likelihood of Ageing Degradation
Medium Likelihood of Ageing Degradation
Low Likelihood of Ageing Degradation

Note: Table 3 is a general guide to aid inspection teams in locating ageing plant equipment. There are, however, many variables such as temperature, pressure, concentration, flow velocity and aeration which affect plant ageing and could therefore change the ratings given. Temperature in particular plays a very significant role in materials performance for any given environment and this table does not take account of any extremes of temperature which may cause significant degradation to materials which are represented here by the low rated boxes.

The ageing mechanisms, where they might occur, and how to recognise and manage them is discussed below.

2.2 Corrosion

Corrosion may be defined as the physical degradation of a material due to chemical reactions taking place on its surface when it is exposed to an environment which will support those reactions.

Wet (Aqueous) Corrosion

Wet corrosion is the most commonly encountered form, it takes place on a susceptible metal surface if water is present in the environment, this also includes water present as vapour in the atmosphere. In the absence of water, wet corrosion will not occur. This is due to the electrochemical nature of the wet corrosion reaction mechanism:

Dry (Hot) Corrosion

Unlike wet corrosion, dry corrosion takes place in the absence of water. It typically occurs at temperatures in excess of 400^{o}C where there is direct chemical oxidation of the surface metal to its metal oxide in the presence of Oxygen.

$$M(s) + O_2 > MO_2$$

2.2.1 Mechanisms

General Corrosion

General corrosion is defined as corrosion which causes a uniform loss of wall thickness which is observed over the entire surface area of the metal exposed to the same conditions. Wall thickness measurements and corrosion rates measured from weight loss coupons, Linear Polarisation Resistance (LPR) or Electrical Resistance (ER) probes can be used to monitor the extent of the internal damage caused by general corrosion. Inspection techniques used to detect this type of damage are discussed in HSE RR509.

Externally, general corrosion is easily identified at exposed structures by the distinctive orange coloured iron oxide corrosion product deposits seen on the surface of uncoated carbon steels. General corrosion is the most common damage mechanism observed in carbon and low alloy steels. Corrosion resistant alloys, however, are typically resistant to this form of corrosion under most conditions.

Localised Corrosion

Localised corrosion is a specific form of corrosion which occurs only at a relatively small area of the total metal surface. Localised corrosion can be extremely damaging to a structure due to rapid degradation and because of the local nature of the attack, the damage can easily pass undetected until a failure occurs. Typically localised corrosion mechanisms are the main form of attack observed for corrosion resistant alloys. However it can also occur with carbon and low alloy steels under certain conditions.

Inspection techniques used to detect this type of damage are discussed in HSE RR509.

Common forms of localised corrosion are:

Pitting corrosion
Pitting is an extremely localised form of attack where the wall loss is confined to a very small area of the surface. The conditions within the pit can quickly become increasingly aggressive causing corrosion pits to rapidly advance through the wall thickness whilst the vast majority of the pipe or vessel wall remains unaffected. This can lead to very rapid failures as the pit quickly penetrates the wall. This form of attack is one of the main forms of corrosion observed in corrosion resistant alloys, however it is also found with corrosion of carbon steels.

Crevice corrosion
Crevice corrosion is similar to pitting corrosion, in that it is likely to be observed under the same environmental conditions that have given rise to pitting. In crevice corrosion the area of localised attack is found within crevices which typically form around and under washers, bolts and seals. The solution within the trapped pocket can become increasingly aggressive and significant localised attack can occur around the crevice.

Galvanic corrosion
Galvanic corrosion occurs at the junction of two dissimilar metals which are in electrical contact with each other. According to their relative positions within the galvanic series one metal will be protected from corrosion at the expense of the other. Depending on the relative surface areas of each metal this form of corrosion can proceed extremely quickly. If the cathodic metal is much larger than the anodic metal surface then the observed corrosion rates can be extremely high as a large cathodic area is driving corrosion at a relatively small anodic point.



Figure 1: Example of galvanic corrosion (in this case dissimilar weld corrosion in heat affected zone)

<u>Velocity related corrosion attack</u>

Erosion Corrosion
Erosion corrosion is a faster form of corrosion attack than would otherwise be expected in a given environment due to high flow conditions or localised turbulence. The increased corrosion damage is caused by the high shear stresses stripping away protective corrosion product films and increasing the transport of the corrodent in the system to the metal surface. The effect is increased if solid particles such as sand are present in the system. This form of corrosion is often observed in copper structures but can affect any material susceptible to corrosion.

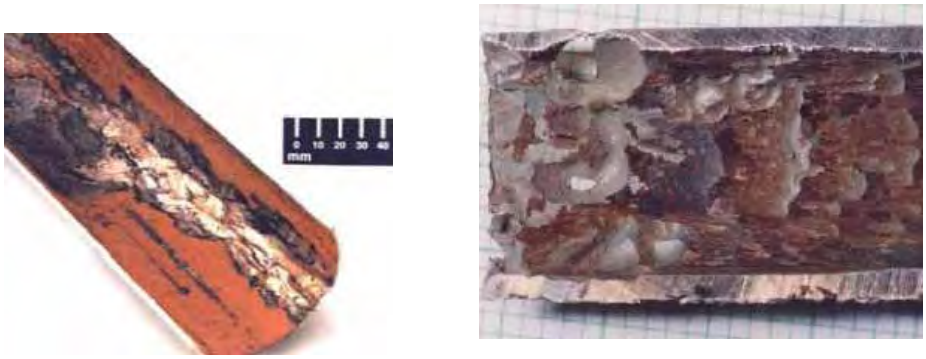


Figure 2: Examples of Erosion Corrosion

Mechanical Damage

Cavitational Corrosion

Cavitational corrosion is a form of mechanical damage which also damages protective films formed on metal surfaces. Cavitation bubbles can form in liquids at areas of a sudden drop in pressure, these bubbles become unstable and can quickly collapse. The pressures and temperatures formed inside a cavitation bubble as it collapses can be extremely high. When a cavitation bubble forms and subsequently collapses on a metal surface this energy is directed onto the surface of the metal which can cause significant metallurgical damage to occur.

Areas where cavitation is likely:

- At the suction end of a pump.
- At the discharge of a valve or regulator, especially when operating in a near-closed (choked) position
- At other geometry-affected flow areas such as pipe elbows and expansions
- Also, by processes incurring sudden expansion, which can lead to dramatic pressure drops

Specific Types of Common Corrosion

Carbon Dioxide (Sweet) Corrosion

Carbon dioxide dissolves in water to form carbonic acid which causes what is known as sweet corrosion. The product of this form of corrosion is iron carbonate which forms as a film on the metal surface. At higher temperatures (+80^{o}C) this film has protective qualities leading to lower than expected corrosion rates at higher temperatures. Sweet corrosion is typically observed as metal wall thinning and shallow pitting. Under high velocity conditions deep elongated pits are sometimes observed.

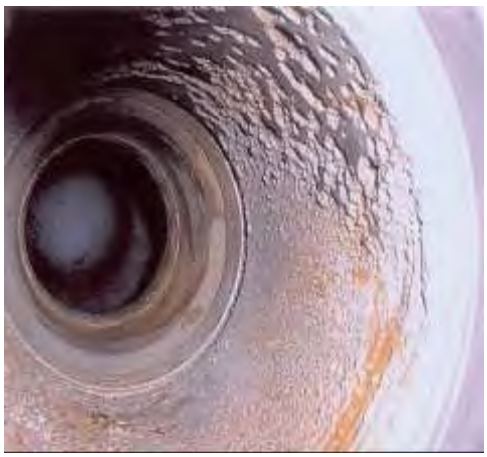


Figure 3: Example of CO_2 Corrosion

Hydrogen Sulphide (Sour) Corrosion

Hydrogen Sulphide dissolves in water to cause what is known as sour corrosion. The product of this form of corrosion is iron sulphide. The low solubility of iron sulphide in water results in the formation of a dark or black corrosion product film that is able to protect the steel surface from general corrosion even in aggressive systems. However due to the conductive nature of the protective film any local break in the iron sulphide layer can result in very severe pitting.

Hydrogen sulphide may also cause hydrogen damage in susceptible steels. The reaction which gives rise to the iron sulphide film releases atomic hydrogen which can then diffuse into the steel where it can lead to the formation of hydrogen blisters or through wall cracking (Sulphide Stress Corrosion Cracking or Stress Oriented Hydrogen Induced Cracking).

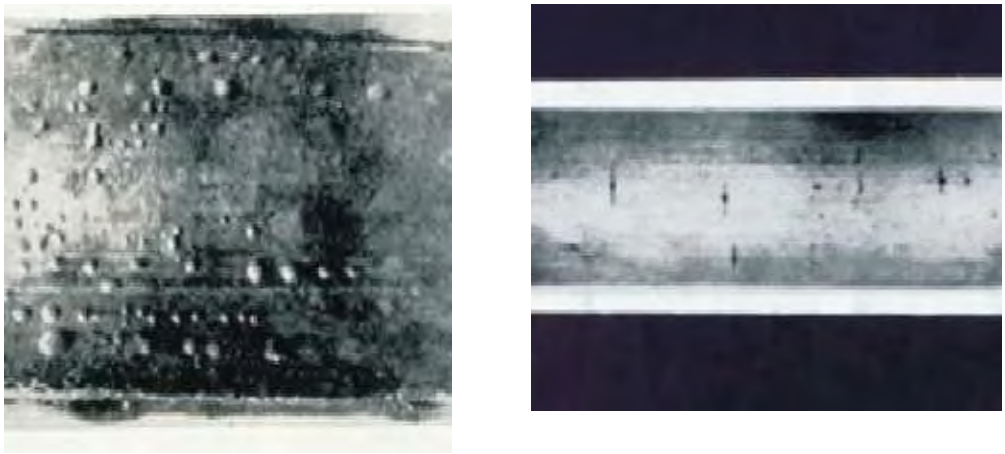


Figure 4: Examples of Sour Corrosion and Cracking

Microbial Corrosion

Microbial corrosion is caused by the action of bacteria contaminated systems, commonly sulphate reducing bacteria (SRB's). It is not the bacteria themselves that attack the metal but the local environments that they create and contribute to that leads to corrosion of the

structure. Microbial corrosion is typically a problem inside pipes which are left with stagnant water, at dead legs and in the bottom of tanks. For microbial corrosion to occur conditions must be suitable to support bacterial life. These requirements include:

- Presence of bacterial life in the system.
- Source of Sulphate.
- Source of Carbon.
- Source of water.
- Anaerobic conditions.
- Close to Neutral pH.
- Suitable temperature and pressure for bacterial life to be sustained.



Figure 5: Examples of Bacterial Degradation

Atmospheric Corrosion

Moisture, oxygen and aggressive species such as sulphate, nitrates and chlorides present in the atmosphere can lead to atmospheric corrosion occurring on exposed structures. Atmospheric corrosion proceeds under the same mechanism as wet corrosion however as a bulk liquid phase is only present during rainfall the corrosion reactions proceed in a thin film of condensed or absorbed moisture on the metal surface.

The major factors that affect the rate of atmospheric corrosion at a given location are the moisture levels and the concentrations of aggressive species in the environment. Marine environments for example with high levels of chlorides present would exhibit significantly greater corrosion rates than inland environments with low levels of chloride. Similarly exposed metal structures in industrial locations with high levels of pollution and therefore higher levels of sulphates and nitrates than rural locations would record higher atmospheric corrosion rates than would be observed in rural locations.



Figure 6: Examples of Atmospheric Corrosion

More examples of corrosion mechanisms and identification of the main mitigation methods for them can be found in the Energy Institute document “Guidance for Corrosion Management in Oil and Gas Production and Processing” ([3], Page 78).

2.2.2 Signs and Symptoms

Corrosion is perhaps one of the more obvious signs of plant ageing because of visible signs of corrosion product, either external or internally within equipment. The nature of many materials, especially carbon and low alloy steels, is to react with the environment by a corrosion process to attain a more stable condition, e.g. metallic iron “wants” to become iron ore again. Many equipment items take account of this in the design process e.g. corrosion allowance so it is important to note that the presence of corrosion products, i.e. rust, does not indicate that equipment is not fit for its service. Rust is merely a sign that the equipment is ageing. The rate of this ageing process and its importance in risk terms are parameters the plant operator should be concerned with.

2.2.3 Susceptibility

All metallic materials are susceptible to corrosion and/or corrosion cracking. Materials termed “corrosion resistant alloys” or CRAs are less susceptible but not immune. This class of materials are protected by a corrosion process that forms a thin layer of metal oxide at the surface. Should the layer be damaged in an environment that does not support re-oxidation, then the material can become susceptible to corrosive attack.

2.2.4 Management Options

Corrosion can be prevented or monitored and controlled. Prevention methods include coatings and/or cathodic protection (often termed “CP”). CP can be achieved either by the use of impressed currents or by connection of sacrificial anodes typically made from zinc or aluminium blocks. If coatings are used there should be evidence of coatings inspection and if CP is employed evidence of maintenance and monitoring of CP effectiveness should be available.

For monitoring and control, management of corrosion is achieved through the following processes:

- Identification
- Detection
- Quantification
- Assessment

Identification usually involves a risk assessment, e.g. RBI plan or may take the form of asset registers arranged to identify those equipment items that are expected to corrode in one way or another.

Detection is the application of a suitable inspection technique, often visual, that can locate the corrosion.

Quantification is achieved by measuring the remaining thickness of material available to contribute to the overall structural integrity of the equipment. In some instances, engineering judgement is applied but this should be documented to a sufficient extent that reasonable next inspection intervals can be deduced.

Whenever corrosion is detected an assessment ([1], Page 74) should be made of its implications for equipment integrity. This assessment should inform any actions that are to be taken in the future including inspections and any repairs/modifications that may be made.

2.3 Stress Corrosion Cracking

2.3.1 Mechanisms

Chloride Stress Corrosion Cracking
Stress Corrosion Cracking (SCC) is observed at susceptible austenitic stainless steels in certain environments. SCC typically occurs in chloride containing environments, for SCC to occur the material must be stressed. The stress does not only need to take the form of an applied physical load to the structure, residual stresses around welds and bends as well as temperature gradients can create stresses that will initiate SCC in a susceptible environment. If either a suitably aggressive environment or a stress is not present then no crack will initiate in the steel, both are required to cause SCC ([3], Page141).

Hydrogen Induced Cracking (HIC)
Often found in sour environments. The presence of H_2S hinders the formation of H_2 gas from the hydrogen atoms produced by the corrosion reaction. Instead the hydrogen atoms are able to enter the steel structure. Hydrogen atoms collect at small voids and inclusions within the steel where they combine to form H_2 gas. The gas pressure of H_2 at these pockets builds up as more hydrogen atoms combine and can become extremely large, leading to cracks forming within the steel structure ([3], Page 82).

Corrosion Fatigue
Corrosion fatigue is the enhancement of the rate of crack growth in a corrosive environment above that which would be expected in a purely mechanical fatigue dry environment. Sources of fatigue include vibration and also the expansion and contraction associated with thermal cycling of equipment.

2.3.2 Signs and Symptoms

SCC is notoriously difficult to detect without the aid of NDT. However, there are tell-tale signs that indicate that SCC might be present in certain cases. For instance, it is well known that pitting corrosion at welds in corrosion resistance alloys is often (though not always) a precursor to SCC since cracks often begin at the bottom of pits. Additionally and in the same alloy group, the surface may exhibit rusty staining with little or no apparent source. This staining is corrosion product originating from within a tight stress corrosion crack.



Figure 7: Examples of Stress Corrosion Cracking

SCC has two distinct phases of development, (i) initiation and (ii) growth. There are no reliable models to predict the time to initiation of a crack and subsequent growth rates are generally unknown and unpredictable. Propagation can be potentially very fast, leaving very little time to act on any observation of the likely presence of a crack.

In most cases, signs of SCC will only be detected as a result of planned plant inspections where the susceptibility to SCC has been identified as part of the planning process, e.g. using risk based inspection. Advice on suitable detection methods can be found in HSE RR509 on Ageing Plant ([1], Page 71).

2.3.3 Susceptibility

The table below presents a list of common alloy/environment systems where SCC may occur [4]. Cracking susceptibility is dependent upon temperature, environment composition, tensile stress level and heat treatment of the specific alloy.

Table 4: Susceptibility Guide to Stress Corrosion Cracking

Alloy	Environment
Aluminium alloys	Chloride solutions
Magnesium alloys	Chloride solutions
Copper alloys	Ammonia + oxygen + water Amines + oxygen + water Nitric acid vapour Steam
Carbon and low alloy steels	Nitrate solutions Caustic solutions Carbonate solutions Alkanolamines + carbon dioxide Carbon monoxide — carbon dioxide + water Anhydrous ammonia + air Hydrogen cyanide solutions
Austenitic stainless steels and some ferritic and duplex stainless steels	Chloride and bromide solutions Organic chlorides and bromides + water Caustic solutions H2S solutions — chlorides or oxidants
Nickel Alloys	Caustic solutions Fused caustic Hydrofluoric acid H2S solutions — chlorides or oxidants
Titanium Alloys	Aqueous salt systems Methanol plus halides Nitrogen tetroxide
Zirconium Alloys	Aqueous salt systems Nitric acid
Sensitised austenitic stainless steels	Water — oxygen (high temperature) Chloride solutions Polythionic acid solutions Sulfurous acid

2.3.4 Management Options

SCC requires the combination of a susceptible material, a tensile stress and an aggressive environment. SCC should be prevented at the design stage by the appropriate selection of materials and control of the stress levels. The unpredictable nature of SCC renders it extremely difficult to monitor and control. If SCC is found it should be repaired or measures taken to fully mitigate the potential consequences of any failure.

2.4 Erosion

2.4.1 Mechanisms

Erosion is the removal of the surface of a material by abrasion. Hard particles impact the surface causing surface wear resulting in loss of material. Erosion is fundamentally different to corrosion because it is not an electrochemical process. It depends mainly on the difference in hardess between the material and the impacting particles and the velocity and impact angle.

Erosion if often found in systems where solids are transported, e.g. systems containing sand, solid products or slurrys. Additionally, erosion can be caused by the impact of liquid particles, e.g. in condensing steam systems ([3], Page 146).

2.4.2 Signs and Symptoms

Prior to failure the most important sign of erosion is the loss of material thickness at certain points in a system or structure.



Figure 8: Erosion of a Pipe Bend

2.4.3 Susceptibility

All materials are susceptible to erosion when impacted by harder particles. Particular susceptibility occurs at positions where there are changes in flow direction and/or velocity, for example at piping bends or choke valves.

2.4.4 Management Options

Management options for erosion are the same as for corrosion. Erosion can be prevented or monitored and controlled in the same way as corrosion and the same assessment methods apply.

2.5 Other mechanisms

A comprehensive list of common damage mechanisms that affect chemical processing equipment can be found in API 571 [5]. Many are common to those found in offshore processing as described in Energy Institute Document "Guidance for Corrosion Management in Oil and Gas Production and Processing" ([3], Page 1).

2.6 Some Key Specific Issues

2.6.1 Corrosion Under Insulation (CUI)

The presence of external insulation coverings on pipelines and vessels can lead to corrosion which is much more severe than would be expected if the equipment was uncoated. There are several reasons for this to happen:

- The insulation creates a creviced area at the surface of the metal which can retain water.
- The insulation itself may absorb or wick water.
- The insulation material may contain contaminates which increase the corrosion rate.
- The insulation hides from view almost all visual evidence of corrosion occurring underneath.

There are two main sources of water under insulation:

- Condensation.
- External sources such as rain, cooling tower discharge, condensate dripping from cold equipment above, steam discharge, process liquid spillage, etc.

Entry of water can be prevented by adequate weatherproofing of the insulation materials. However it is not possible to completely prevent the ingress of water vapour from the atmosphere and therefore condensation can form on the metal surface underneath the insulation. Additionally damaged and/or inadequate weatherproofing can lead to water penetration.

Forms of Corrosion found under Insulation

Moisture trapped under insulation would be expected to cause general corrosion of carbon steels at areas of uncoated pipework. The level of general corrosion observed would depend upon the existence, quality and condition of the coating system applied to the steel below the insulation. At stainless steels localised corrosion would be expected particularly if chloride contamination is present under the insulation which may lead to localised corrosion in the form of pitting and crevice corrosion. Additionally, cracking in the form of stress corrosion cracking or corrosion fatigue may be observed in susceptible areas.



Figure 9: Examples of Corrosion Under Insulation

Inspection of insulated equipment

Inspection is difficult as the metal surface is covered by insulation. Complete removal of the insulation would be needed to allow for a thorough visual inspection of the metal surfaces for CUI, however this is usually impractical. Visual inspections should begin by identifying areas where damage and breaks to the weatherproofing potentially allowing water ingress are visible. Additionally swollen or misshapen insulation can indicate the presence of rust built up below the insulation.

If no areas of damaged weatherproofing are visible then inspections should concentrate on the following areas:

- Surfaces exposed to frequent hot to cold cycles.
- Cold temperature equipment with parts which project through the insulation.
- Interfaces between hot and cold equipment.
- Horizontal pipe work, especially where there are joints and branches extending from the base.

Inspection Techniques

The standard inspection technique is to remove small sections of the insulation at regular intervals across the pipework to allow inspection of the condition of the metal surface below. Appropriate techniques for inspection of pipework, once a small spot of insulation has been removed, include:

- Visual inspection of the surface for evidence of dampness, coating defects and surface rusting.
- Ultrasonic wall thickness measurements can be taken to asses the level of wall loss due to general corrosion.
- For Stainless Steels where no general corrosion would be expected a visual inspection for evidence of localised areas of rust staining indicating the presence of

pits or crevice corrosion can be conducted and a technique such as Dye Penetrant used to identify SCC cracks in the structure.

Inspection of pipework by spot removal of insulation poses two problems. Firstly the removal of some insulation sections creates a break in the weather proofing and a potential entry point for water ingress in the future. Once the inspection is complete the insulation must be carefully replaced and sealed to prevent water entering at the inspection points. Secondly only a small percentage of the structure can be inspected this way which has the potential to miss defect areas. Therefore there are some inspection techniques that allow the entire structure to be inspected with either minimal removal or no removal of the insulation required. A selection of these techniques are summarised below:

Flash Radiography can be used to carry out preventive checks on insulated pipelines, vessels and equipment with diameters up to one meter. An image is produced on medical film which is used to measure any wall thickness loss due to CUI.

Guided Wave Ultrasonic measurements can be used to inspect for both internal corrosion and corrosion under insulation. A small portion of the insulation needs to be removed to attach the probe ring to the structure. The ring transmits ultrasonic waves through the structure. The echo of these waves is then used to assess the wall thickness. The waves are able to travel across straight sections, bends supports, welds and even buried or otherwise inaccessible sections.

Profile Radiography: Exposures are made to a small section of the pipe wall from above the insulation. This technique is able to measure wall thicknesses of pipelines up to 10 inches in diameter over relatively small areas of the surface. Measuring larger pipeline diameters is possible but it can be very technically challenging. Additionally the radiation source can pose safety problems to the operator.

The following techniques are applicable to assessing general corrosion only;

- Pulsed Eddy Current
- Digital Radiography
- Infrared Thermography
- Neutron Backscatter

Inspection Techniques for Pitting
External pits can be identified visually by tell tale rust stains surrounding the pitting.

Internal pits can be visually inspected in the case of large vessels where entry is practical..

Pit Monitoring:
Electrochemical noise measurements can be used to monitor pitting formation in real time. Additionally, pitting examinations of weight loss coupons can give an indication if pitting is taking place on the internal surfaces of the structure.

2.6.2 Machines & Rotating Equipment

Loss of containment from age related deterioration of machinery and/or rotating equipment can occur in the same way as for static equipment. The range of mechanisms that can cause such integrity failures are essentially the same as those for static equipment but the dynamic nature of machines can exacerbate the rate of deterioration in some instances. Some examples from HSE RR509 include:

- 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.

The types of machinery and equipment used in the chemical industry are very similar to those utilised offshore. HSE Research Report 076 on "Machinery and Rotating Equipment Integrity Inspection Guidance Notes" [6] provides a comprehensive description of many of the equipment types in common use and identifies many of the issues, including ageing issues that can affect the equipment.

2.6.3 Fired Heating Equipment

Fired heating equipment is subject to ageing both on the fire-side and the process side. Normal ageing processes discussed above apply, e.g. corrosion, stress corrosion cracking etc, but are added to with specific ageing mechanisms related to the high temperatures on the fire-side, e.g. high temperature oxidation and creep. In addition, significant thermal cycling can give rise to fatigue over a period of time and metallurgical changes can occur because of prolonged service at high temperatures.

More detail on potential damage mechanisms and methods of inspection that should be used can be found in API Recommended Practice 573 on "Inspection of Fired Boilers and Heaters" [7].

2.6.4 Non-Metallic Materials

Composites do not corrode per se but can be subject to a number of degradation mechanisms in-service including physical ageing, mechanical ageing and chemical ageing. The consequence of these can be a reduction of 20 - 40% or greater in the strength characteristics of the polymer during the lifetime of the component and introduction of damage including matrix cracking and delaminations. This is handled in design codes by use of regression curves based on short term and longer term (typically 1000h) tests to determine the *qualification pressure* for the component and the allowed *operating pressure* over the design life.

There is concern about whether such methods of life assessment are sufficiently robust, given the increasing diversity of applications in which composites are applied. In contrast to steel vessels or pipework where non-destructive methods such as ultrasonics, electromagnetics and radiography are widely applied, very little inspection other than visual inspection or pressure testing is currently undertaken on composite components in the chemical, process and petrochemical industries.

There are limitations in the testing methods used to estimate the regression curve or degradation that may occur with ageing in service. Most studies are in water rather than organic solvents or the other fluids that are seen in service. Immersion testing rather than

single-sided exposure mechanisms may cause mass gain as well as loss; so single-point data is of limited use in prediction of longer term degradation. Service components suffer environmental degradation from the surfaces; hence the degradation seen in immersion tests may be worse than seen in practice.

A diversity of environments can be encountered in the chemical and process industries. These can cause damage to both the matrix and the fibres. It is important that the resin and fibre types are correctly selected for the application to maximize the resistance in service. In oil industry applications a corrosion resistant layer (or veil) containing more resistant fibres and gelcoat is commonly applied to the surface. Similar practice may be used in chemical applications. Such layers are effective at preventing environmental damage but are relatively thin (~200um). It is important to confirm on visual inspections that excessive grazing of the gel coat has not occurred and that damage has not occurred to these protective layers

Areas of bend, variations in thickness, support or change in geometry are particularly susceptible to damage or degradation in composite systems. These may encounter local stress concentrations and care is needed in design to ensure these can adequately support the operating pressures of the piping or vessel and that the allowance made in regression curves for ageing is sufficient.

There are particular issues for lined or painted glass fibre reinforced epoxy (GRE) vessels or pipework. If a lining is used then a compromise may be made on the resin and fibres used in the GRE vessel. These may not be as resistant as would be used if the GRE was exposed to the environment. It is important in this case to monitor the lining condition since lining failure could lead to degradation and failure of the GRE vessel in a shorter timescale than might typically occur for an unlined vessel exposed to the same environment. Composite components are often painted for cosmetic reasons. This may provide some additional protection to the external environment. A consequence of painting is that it is no longer possible to inspect the component visually using internal illumination, a standard method. In this case detection and monitoring of service damage may be more difficult.

A more detailed description of the types of failure mode observed in non-metallic materials in containment service is provided in Appendix 2 of the Phase 1 Report [2].

2.6.5 Concrete Support Structures

Concrete, especially reinforced concrete, is as susceptible to ageing effects as any other material. Some common causes of defects are illustrated in Figure 10 below [8].

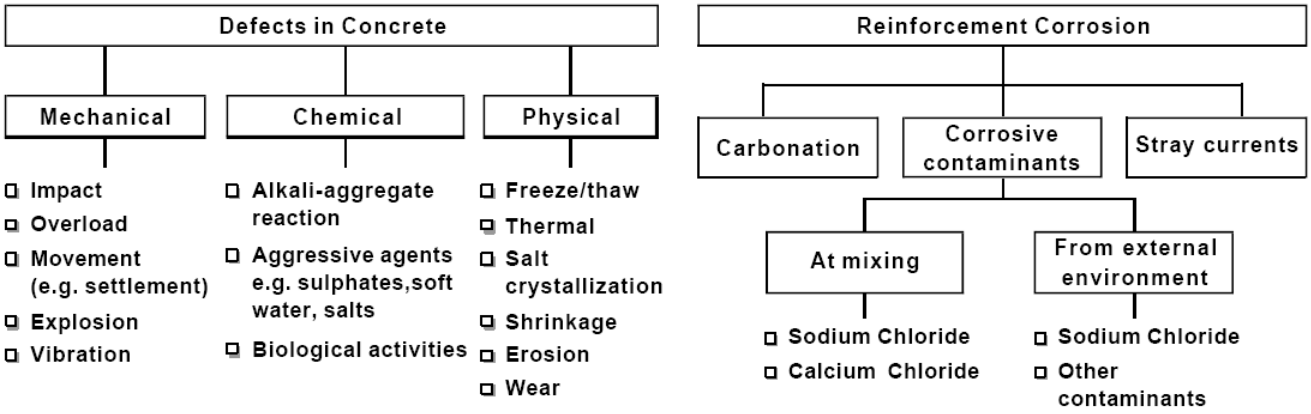


Figure 10: Common Causes of Defects in Concrete Structures

Monitoring and assessment of such defects is covered by EN 1504 [9]. Where such structures are employed in safety critical service, e.g. support of pressure containing vessels etc, evidence of monitoring and assessment of age related degradation should be available.

In cases where cathodic protection (CP) is applied to protect the steel reinforcement within a concrete structure evidence of periodic monitoring of CP effectiveness should be apparent. For more details on CP of steel in concrete please refer to BS EN 12696 [10].

2.6.6 Glass Reinforced Plastic (GRP)/Glass Reinforced Epoxy (GRE) Tanks

Glass-reinforced Plastic/Epoxy is a composite material which is commonly used for tanks and pipes in areas that are not normally exposed to high temperatures or pressures, often this material is used for storing and transporting water. GRP/E is manufactured by forming tiny glass fibres into an overlapping mesh within a mould with a thermosetting plastic or epoxy resin placed between the layers. Curing of the plastic or resin then produces a lightweight, strong and generally corrosion free material. However it is a misconception to believe that once installed components made from this material require no maintenance or inspections and are suitable for indefinite service. Although none of the aqueous corrosion mechanisms associated with steel structures affect GRP/E materials there are several damage and degradation processes for these materials and also the possibility of defects going undetected during the manufacturing process or mechanical damage inflicted after installation.

Typical damage mechanisms for composite materials can include wall thinning due to exposure to chemicals which are incompatible with the resin used in manufacture. This can expose the underlying glass fibres and weaken the structure. Erosion and cavitation are two other internal wall thinning mechanisms which can also damage these materials internally. Delamination of the composite layers can occur due to thermal or chemical ageing of the resin layers or because the glass fibres have not been sufficiently wetted by the resin during manufacture. UV exposure eventually results in the breakdown of the external laminate layer known as “Chalking” although this usually only damages the outer surface layer. Additionally blisters can form between laminate layers causing bulging at the surface. Fatigue cracks can occur which propagate through either the resin and glass fibres or only the resin layer (matrix cracking). Unlike metals however, the crack initiation is always mechanical in nature. Cracks are usually observed at joints due to poor connections and the over-torquing of bolts.

The majority of defects in GRP/E structures can be identified with an external visual inspection. If internal inspections are possible then internal wall thinning is clearly identified by the exposed glass fibres that are left behind when the resin is lost. If an internal inspection is not feasible then ultrasonic wall thickness measurements can be taken to assess any damage. As with metal structures radiography may be used to identify cracking.

A useful source of further information is ISO 14692 Part 4 [11] which examines the fabrication, installation and operation of GRP piping. Many of the issues covered in the standard are equally applicable to GRP components other than piping, including the guidance provided on inspection of this class of materials.

2.6.7 Buried Pipes

Metallic pipes and tanks buried below ground would, if left unprotected, undergo external corrosion depending on the material composition and the local environmental conditions. In order to prevent corrosion and subsequent failure of the pipe or tank, the exterior surfaces of buried metallic structures are typically protected by both a coating and a cathodic protection system.

Where equipment is protected by a cathodic protection system then monitoring of the electrical potential of the protected structure at an adequate number of points along the buried pipeline or around the tank will give an indication that the cathodic protection system is functioning correctly in order to protect the outer surface of the structure. However this will not give any information as to the effect of corrosion process's occurring internally or identify any defects which may be present within the structures.

Inspection of buried pipes and tanks is obviously much more difficult than for exposed structures. Visual inspections, and NDT techniques are not usually possible without prohibitively expensive and disruptive excavations being carried out around the buried structure. Inspections are usually only possible in the case of underground pipes which run within a tunnel or trench. Depending on the accessibility, a visual inspection and other NDT techniques may be carried out in the same way as for structures above ground.

For large underground pipelines which have been built to accommodate intelligent pigs, then this is the best technique to inspect the internal surface of a pipeline. Pigs are able to make continuous ultrasonic wall thickness measurements over the entire length of the pipeline. This is not possible however in small sections of pipes that might, for short distances, pass below ground. This may typically be observed where pipes cross underneath roads. In order to inspect these pipes a technique known as Guided Wave Ultrasonics is able to make wall thickness measurement up to 25m along a pipe from the location that the equipment is attached to an above ground section.

More information on the degradation and protection measures, specifically cathodic protection, that can be applied to buried steel structures can be found in API Recommended Practice 1632 [12].

3.0 Management of Ageing

Plant ageing should be managed as part of a well structured Health, Safety and Environment Management Systems (HSEMS). In many cases the term “ageing” may not be mentioned explicitly but management of ageing issues should be catered for in the management of system integrity and functionality and covering all asset types.

A well structured and maintained HSEMS document is a means of identifying and setting down a commitment to how a business will manage health, safety and environmental issues. Larger businesses will develop such a document and refer to the many standards, procedures and methods by which they will maintain performance across all sections of their business.

Many small and medium sized businesses will also have the required standards and procedures documented but they may not have these requirements organised into a document which explains how these requirements will be implemented and maintained. These standards and procedures will refer to both operational and process health and safety issues.

The identification and management of ageing plant issues in relation to process safety is recognised in a number of key risk control systems which must be identified and documented in order that they are regularly reviewed and updated. Key elements include:

- Maintenance Management Systems
- Asset Management and Integrity Systems
- Audit and Inspection regimes
- Risk Assessment Management processes
- Management of Change procedures
- Permit to Work
- Responsibilities and Communications
- Training and Competence development

A key stage in managing ageing plant issues in any business is identifying what hardware and resources the business has; this would identify the potential extent of the ageing issues and the way in which it will be managed. This should be linked with an action plan that will encompass implementation and monitoring of the risk control systems to avoid major incidents.

In recognising ageing mechanisms, businesses can identify key performance indicators (KPIs) which can be monitored to identify how effectively the risks are being controlled. These indicators would form part of any Action Plan with target completion of leading indicators normally within one year, and with reviews on progress throughout the year.

Both leading and lagging indicators must form a balanced approach to managing the risk control systems to ensure the risks are controlled to an acceptable level, the approach to this is explained fully in the HSE publication HSG 254, Developing Process Safety Indicators [13].

Every business is different and therefore the number and focus on KPIs will differ. There is no right system for all and it is a requirement of the management team to identify the key process indicators they wish to monitor in relation to ageing plant issues and the control of major hazards.

The following are just some of the key indicators to be considered.

Leading Indicators

- Number of planned inspection,
- Number and frequency of audits
- Planned replacement schedules for plant and equipment
- Number of Emergency Response exercises planned.
- Planned number of tests done on safety critical equipment.
- Training plans for identified staff and staff numbers attending.
- Planned procedure reviews

Lagging indicators

- Number of major failures of plant and equipment.
- Number of uncontrolled releases of product.
- Number of reworks to maintenance activities
- Number of outstanding audit/Inspection action items.
- Number of alarm/instrument failures during testing
- Number of incidents when working under a Permit to Work system
- Number of incidents due to Human Error.

A number of major incidents in the oil and gas and major hazard industries over the past years have been caused by failures of plant and equipment, the condition of which has deteriorated over a period of time for various reasons. Recognising the ageing mechanisms that affect the process and then introducing and maintaining a structured management system approach to mitigate the potential for failure will significantly reduce the incidents of major accidents in the industry.

As an illustration, in one incident a redundant branch pipe, which was still attached to the live main transfer line, fractured due to vibration fatigue. The branch had been in place since the 1950s and had been left unsupported after a change to its configuration pre 1987. In a period of four years from 1998 there had been an increasing number of shut downs and start ups which added further fatigue and shock loading to the branch line, during this time a number of incidents had occurred in which vibration was a relevant issue.

The pipework was inspected for corrosion only and there were no proactive surveys for dead legs/redundant drains etc.

The key Risk Control Systems missing from this operation would be as follows.

- Management of Change procedures (Not recognising the effects of change when the branch was made redundant)
- Asset Integrity Management System (Weak assessment approach that did not include dead legs/redundant drains etc).
- Risk Assessment/Management processes. (Not identifying the risks of leaving unsupported redundant pipework tied to a live system)
- Audit and Inspection Regimes.(Not identifying the potential for failure of pipelines due to vibration. Poor inspection procedures).
- Procedures (Weak procedures that did not identify and act on a trend of an increasing number of vibration related incidents over a period of two years prior to the incident)
- Training and Competence (Staff did not recognise the potential for failure of the branch during the continuing maintenance and operational activities of the plant).

A key reference document is the HID CI, SI Inspection Manual [14] which offers overall guidance on the completion of inspections in the Chemical, Oil and Gas onshore sectors. Table 5 summarises the safety management and risk control systems in relation to ageing plant.

Table 5: Safety Management and Risk Control Systems in relation to Ageing Plant.

Risk Control System	Considerations	Ref.
Plant design and modification. *(Leadership & commitment)*	• An Asset Integrity Management Policy communicated and understood at all levels. • Design standards/codes of practice monitored, updated and understood to recognise the potential effect of ageing. • Performance of assets are monitored and discussed at senior level (Improvements, failures, anomalies etc.) to recognise a potential ageing issue. • Contractor and third party standards clearly defined and tested.	*HSG65 Chp 3 & 4 [15]* *HSE RR509 Plant Ageing Chp 2 [1]*
Responsibilities and Communication *(Organisation & responsibilities)*	• A clear organisational structure with identified responsibilities set out in job descriptions. • Clear internal and external communication routes through regular Engineering/Operational meetings, Contractor/Third Party Management meetings etc.	*HSG65 Chp 2 & 3* *HSE RR509 Plant Ageing Chp 2*
Training and Competence development *(Resources)*	• A competency development programme for critical staff containing the ability to recognise ageing mechanisms. • A structured training plan in place. • Job continuity plans to retain job knowledge and operational skills.	*HSG65 Chp 3* *HSE Human Factors Briefing Note No2 – Competence [16]*
Procedures *(Documentation / Planning)*	• Technical Safety Reviews on critical equipment. • Operational procedures that interface with Maintenance Management to avoid repeat work and subsequent increased stress and reaction of plant to downtime. • Clear leading/lagging KPIs monitored on a regular basis to track performance. • Proactive approach to identifying potential incidents and near misses which may identify ageing issues. • The development of a Plant Defect Reporting System	*HSG65 Chp 4* *HSE Technical Measures Document – Maintenance Procedures [17]*
Risk Assessment /Management processes *(Hazard & Effects Management)*	• Risk Assessment programme relating to the impact of failure and the effect of process change • Hazard identification and fitness for service reviews to identify the effect of ageing mechanisms such as wear, corrosion, damage, vibration, pressurisation, atmospheric exposures etc. • Risk based inspection programme identifying ownership and rational for change. • Accident/incident investigation procedures with clear action tracking and close out procedures.	*HSG65 Chp 4* *HSG254 Risk Control Systems [13]*

Asset Integrity Management Systems *(Implementation)*	• AIMS plan and procedures in place to identify HSE Critical plant and equipment. • Clearly identified and accessible Asset Register documentation to ensure action is taken at the correct intervals. • Reviewed at clearly defined intervals to ensure correct data is maintained.	*HSE RR509 Plant Ageing Chp 4*
Management of Change procedures. *(Implementation)*	• A clearly defined Management of Change procedure. • Clear lines of responsibility and communication to agree and implement change. • Consideration of organisational change and its influence on systems and human factors.	*HSE RR509 Plant Ageing Chp 2* *HSE Briefing note 11 - Organisational Change [18]*
Maintenance Management Systems *(Implementation)*	• A well structured and understood Maintenance Management and Inspection System that interfaces with operations. • Replacement policy in place for HSE critical plant and equipment.	*HSE RR509 Plant Ageing Chp 4*
Audit, Review and Operational Inspection regimes *(Audit & review)*	• An audit programme is in place to ensure all elements of a management system related to the controlling of ageing plant and equipment issues are maintained. • A operational inspection regime which highlights the need to identify ageing mechanisms such as corrosion, external damage, vibration, exposure to the elements, impingement of harmful releases, identification of dead legs, etc. • Clearly developed corrective action plans with close out tracking systems.	*HSG65 Chp 6* *HSE RR509 Plant Ageing Chp 4.5*

The development of a structured Management System with reference to key elements relating to potential Ageing Plant and Systems issues is vital to reduce further the potential for Major Accidents in the Chemical, Oil and Gas Industry.

4.0 EC&I Specific Guidance

4.1 Introduction

This section is intended to provide high level guidance regarding technical and managerial issues surrounding ageing Electrical, Control and Instrumentation (E/C&I) systems and equipment.

Examples of such systems and equipment include:- relays, switchgear, electric motors, starters, level sensors, pressure sensors, transmitters, PLCs, DCS, SCADA, valves, pumps, etc.

In safety systems, these systems and equipment are employed to provide emergency shut-down systems, trips, alarms etc, which either separately or in combination with other systems ensure safety in process plant, e.g. overfill protection systems for bulk storage tanks.

Any electrical, control or instrumentation system is potentially within scope if either
(a) its purpose is to ensure that the plant or equipment stays within safe operating limits, or
(b) its failure could cause a dangerous situation.

In terms of managing major hazards, it must be clear which of these E/C&I systems are safety critical. This can be established through a variety of techniques including SIL assessment, HAZID and HAZOP studies, and the identification of safety critical systems and the setting of performance standards for these. SIL assessment techniques are described in, for example, BS EN 61508-5, *Functional safety of electrical /electronic/programmable electronic safety-related systems*, *Part 5: Examples of methods for the determination of safety integrity levels* [19].

E/C&I systems and equipment can be affected by the same degradation mechanisms as mechanical equipment, such as corrosion, erosion, fatigue, etc. However, they can also be subject to more E/C&I specific degradation mechanisms. These include physical mechanisms such as impact damage or surface abrasion, overheating/ burn damage, blockage, fouling or poisoning or the formation of 'tin whiskers' or dry joints, and instrumentation aspects such as instrument drift. Poor quality control of plant painting activities can (as with mechanical plant) affect E/C&I equipment, for example the painting of flameproof glands, or painting over instruments. There are also significant issues relating to the relatively shorter working life of E/C&I systems compared to some mechanical plant, and the degree to which some types of instrumentation and control systems, and the software that is used in them, can become obsolete or difficult to support.

On the other hand, software-based E/C&I systems can provide significant advantages to safety in terms of improved control and diagnostic information, as well as providing economic advantages compared to older style analogue systems.

Since the 1990s, international standards such as BS EN 61508 and IEC 61511 *Functional safety – Safety instrumented systems for the process industry sector* [20] have provided a lifecycle-based framework for successfully deploying such systems and a number of Guidance documents have been produced, for example EEMUA 222, *Guide to the Application of IEC 61511 to safety instrumented systems in the UK process industries* [21].

The Guidance set out here draws on these standards and provides further guidance on issues particularly related to "ageing" and how they can be managed effectively.

In determining how well E/C&I ageing plant issues are being managed there are certain key themes, as follows:

1. Is the E/C&I equipment "ageing"?
2. Is there an understanding of the safety significance of the E/C&I equipment?
3. Are there plans for the likely replacement of at least some of the E/C&I equipment during the lifetime of the whole plant? Is there an awareness of the technical and resource issues?
4. Are there adequate arrangements for Maintenance and Procurement of modern E/C&I equipment?
5. Are there adequate arrangements for Management of Change (MoC)?

This guidance is therefore structured around the above key themes to help promote awareness and understanding of the issues.

Specialists may wish to refer to more detailed guidance which deals exclusively with E/C&I matters. The guidance, E/C&I Plant Ageing: A Technical Guide for Specialists managing Ageing E/C&I Plant [22], is being developed and will be published in the near future. It will also include a discussion of ageing mechanisms and how to recognise them, a list of relevant standards, and references to other relevant literature.

4.1.1 What is "Ageing E/C&I equipment"?

There is no precise definition for "ageing E/C&I equipment" but, in general terms, the overall definition of ageing offered in Section 1.3 is considered sufficiently broad in nature to encompass E/C&I ageing mechanisms.

Some specific age related E/C&I issues are discussed below:

4.1.1.1 C&I Equipment Lifecycles

With care, even quite sophisticated control and instrumentation (C&I) equipment can be kept working to a remarkable age. Other equipment may need replacing after quite short timescales. Digital (or software–based) equipment shows a tendency to have significantly shorter lifecycles. For planning purposes, the lifetime of a DCS/SCADA can be taken as 15 to 20 years. However in some instances the lifetime may be as short as 10 years, while with care and effort some DCS/SCADA systems can be kept operational for longer periods.

DCS/SCADA equipment is not normally classified as safety-critical, but there may be ageing-related unreliability of the DCS/SCADA which will increase the demand rates on the safety-critical systems.

E/C&I equipment life can be extended if good support arrangements are in place either from the Original Equipment Manufacturer (OEM) or a specialist contractor. However, in general, the following principles apply:

- C&I obsolescence is usually ultimately driven by spares availability.
- Older C&I equipment will often be analogue.
- Almost all new equipment is digital or software-based.
- Demonstrating the safety of new digital equipment requires significant effort but in return can provide significant safety advantages (as outlined in section 4.1).

Having the capability to assure the specification and safety performance of new digital equipment is therefore a key factor in managing the obsolescence of older C&I equipment.

A related issue is the ability to support and maintain any software associated with C&I equipment. It can be particularly difficult to find competent people with the skills and experience to safely maintain and make changes to older programmable logic systems and control software. This applies especially where documentation is incomplete or inaccurate, or where software languages used in older equipment have become obsolete.

4.1.1.2 Cable Ageing

Cable ageing is dependent upon the type of cable (e.g. whether or not it is armoured), the type of insulation (e.g. some types of insulation degrade more rapidly when exposed to sunlight), the potential for mechanical or thermal damage, and humidity. Well-specified cabling can survive for twenty years or more outdoors and for thirty years or more indoors.

One reference source [23] suggests 60 years as the accepted economic life for cables. This benchmark value is of course dependent on many factors, such as environmental factors and physical damage. Appropriate reviews should be carried out periodically.

4.1.1.3 High Voltage (HV) Equipment Life Expectancy

High Voltage (HV) equipment generally comprises switchgear, transformers and rotating equipment (motors and generators). Failures of HV equipment can be sudden, severe or even catastrophic. A number of sophisticated condition monitoring techniques are available for monitoring the state of ageing HV plant.

Benchmark values for the life expectancy of HV equipment have been published (see Ref. [23] for details), as follows:

Transformers (132kV)	30-40 years
Transformers (<132kV)	50 years
Switchgear	30-60 years

These benchmark values are in no way assured. They are very dependent on many factors, such as environmental factors, standard of maintenance, and physical damage. Appropriate reviews should be carried out periodically. Some HV equipment may only be operated infrequently; in those cases the equipment should be subject to risk assessments to review degradation mechanisms since the last operation.

4.1.2 Significance of E/C&I Equipment Lifetimes

The significance of the above notional values for equipment lifetimes is that, whereas HV equipment may (with proper maintenance) last through the entire life of a typical plant (say 30 to 40 years), it is unlikely that the same can be said for C&I equipment. Hence operators should expect to have to carry out at least one mid-life refit of C&I systems.

4.1.3 Issues related to Ageing E/C&I Equipment in incidents

The Ageing Plant Phase 1 report [2] includes an account of a data review to identify where ageing was a significant factor in major loss of containment accidents. With regard to E/C&I the following conclusion were drawn;

- E/C&I issues are a significant factor in around 10% of major accidents in the MARS European Major Accident database.

- The biggest single factor in all E/C&I failures is associated with Level Detection, often resulting in vessel overfill and loss of containment.
- Other significant causes of E/C&I failure include Loss of Site Power, Lightning/Earthing and Software failures, including examples of issues caused during upgrading to modern DCS control systems.

The review concluded that there is a need, on all high-hazard plants, for very firm links between:

(i) the Safety Report (identifying the Safety Critical Elements (SCEs)) and
(ii) the Maintenance, Inspection and Test (MIT) schedule (taking each and every SCE and going right down to individual instruments, logic elements and output devices, also addressing potential initiating events like loss of supplies and lightning strike, and defining specific test requirements and frequencies).

The MIT schedule, based on the Safety Report, needs to be matched with KPIs measuring the backlog of safety-related maintenance, to make sure that management can see that the appropriate MIT work is being completed.

4.2 E/C&I Maintenance Management

Good maintenance management processes and practices are central to ensuring that ageing safety-related E/C&I systems and equipment continue to operate reliably and with good availability. These issues are dealt with in detail in the referenced standards and guidelines, but in summary key aspects of maintenance management are as follows:

1. Maintenance Planning
    a. Is E/C&I equipment classified according to its safety function?
    b. Are suitable performance standards established?
    c. Are there Maintenance, Inspection and Testing (MIT) plans in place?
    d. Is the MIT backlog monitored?
    e. Are there suitable robust arrangements for the control and management of overrides?

2. Procurement - Spares and Support Issues
    a. Spares availability and storage
    b. Contractual arrangements
    c. Change control
    d. Contingency planning and related QA issues

3. KPIs for Management of C&I Ageing – lagging and leading indicators

4. Plant History
    a. Are equipment failure data records kept?
    b. Is there learning from others' failure?

5. Specific Ageing and Failure Mechanisms

Key aspects are discussed further below.

4.2.1 Maintenance Planning

Good maintenance planning is absolutely key to the lifecycle management of safety-related E/C&I equipment. Figure 11 presents a diagram showing how the Safety Report should relate to maintenance practices.

The key aspects are:

- Safety-related E/C&I equipment should have defined performance standards.
- Safety-related E/C&I equipment should have Maintenance, Inspection and Test (MIT) plans in place.

Testing (and proof testing) should be designed to confirm that safety-related functions are being performed properly and most importantly that there are no unrevealed failures (see HSE CRR 428, *Principles for proof testing of safety instrumented systems in the chemical industry* [24]).

- Test frequencies should preferably be risk-based.
- Non safety-related E/C&I systems, if they fail, may challenge safety-related equipment.

- Good practice is to have a maintenance policy document for E/C&I equipment.
- There should be clear evidence of well-planned MIT arrangements and activities, including evidence (KPIs) that the maintenance backlog is being properly managed.
- There should be robust managerial controls over the assessment, approval, application and removal of all overrides.

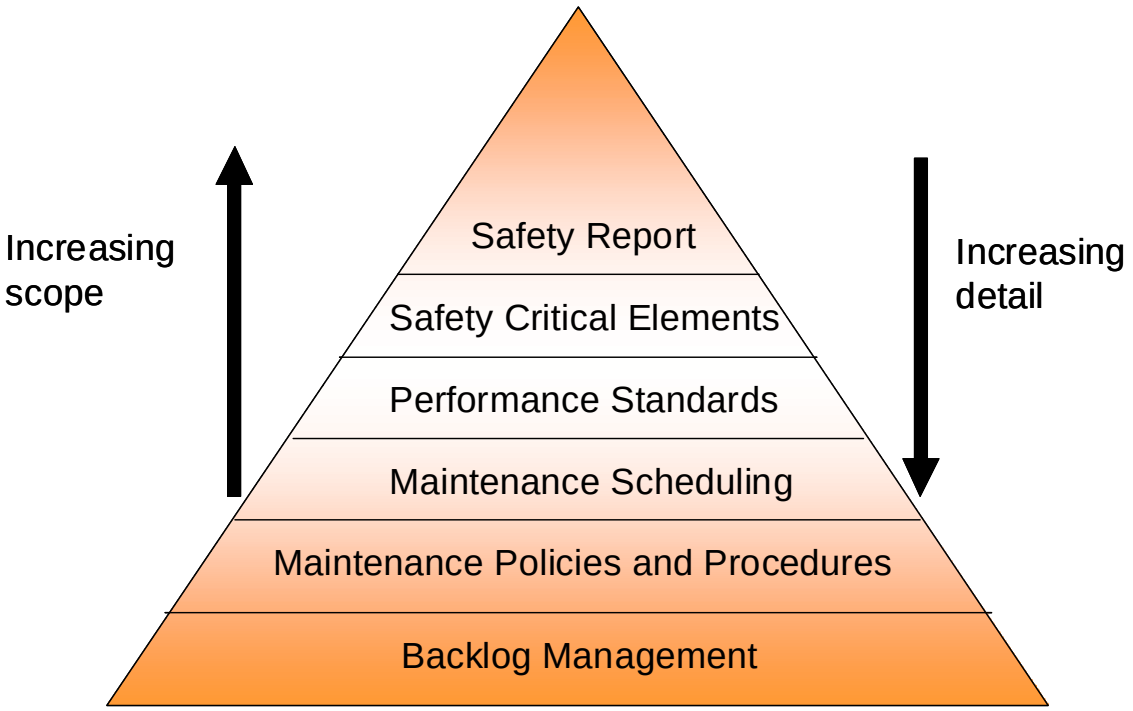


Figure 11: The relationship between the Safety Report and maintenance practices

4.2.2 Procurement – Spares and Support Issues

So-called E/C&I 'ageing' or obsolescence in practice is most often determined by spares availability. OEM contracts may expire after a given number of years, and spares may no longer be available. However, E/C&I equipment can in some instances, and with care and forethought, be operated safely well beyond this point. Issues to consider include:

- Adequate spares holding, in good storage conditions.
- Long-term support contracts with the OEM.
- Specialist contractors for some component repairs.
- Awareness of the risk of lack of change control over time in the supply of spares from the OEM – especially for digital components.
- QA issues around buying second-hand components or potentially faked components.

4.2.3 Plant History and Other Experience

It is important to identify and record the performance of E/C&I equipment including any in service faults or failures and problems discovered during testing and inspection. Some form

of accessible record of plant component failures is highly desirable. Such a record achieves, inter alia, the following:

- It enables the Maintenance Department to identify where re-working is needed and where repeat failures occur, thus enabling smarter solutions to plant problems and feedback to suppliers to improve or change designs
- It improves awareness and accuracy of component reliability data and failure modes.
- It enables Technical or Engineering Departments to identify those components which have a significant adverse contribution to plant availability and safety.
- If relevant, it enables more accurate Quantified Risk Assessments of the plant.

Ideally, an organisation should also have access to cross-industry sources of information which improve awareness, and enable learning from, incidents and accidents which have occurred elsewhere.

4.2.4 KPIs for Management of E/C&I Ageing

Extensive advice on the use and development of process safety KPIs is available elsewhere – see for example:

- HSE, *Developing Process Safety Indicators*, HSG 254 [13]
- Process safety KPI downloads available from www.aiche.org/ccps/metrics

Both leading and lagging indicators should be used as KPIs. Lagging indicators measure *outcome*, whereas leading indicators measure *processes or inputs that are needed to deliver the desired safety outcome.* In general, lagging indicators are easier to measure and more reliable, but they only show what has already happened, whereas good leading indicators should forewarn of future difficulties.

Table 6 presents some ideas for Process KPIs related to E/C&I ageing.

Table 6: KPIs for management of E/C&I ageing

Item	Description of issue	Detail
1	Need for leading and lagging indicators	Lagging indicators measure *outcome*. An outcome is the desired safety condition that management arrangements should seek to deliver. Lagging indicators show when things have been going well or badly, e.g. by measuring incidents or accidents. Leading indicators measure *processes or inputs that are needed to deliver the desired safety outcome*, e.g. by measuring whether MIT work has been completed to schedule.
2	Lagging indicators for E/C&I	Examples: 1. Number of defect reports per month for E/C&I equipment 2. Rising trends in failure rates for specific components or systems 3. Overrides: 'spot' values of the total number of overrides extant across the plant 4. Overrides: total number that have been newly applied during (say) the last month

		5. Incidents arising from E/C&I failures 6. Safety or business-critical system downtime due to E/C&I failures
3	Leading indicators	Examples: 1. E/C&I planned maintenance backlog 2. E/C&I reactive maintenance backlog 3. Maintenance support – remaining duration of existing contractual support 4. Spares holding for critical components 5. Management of Change (MoC): numbers of E/C&I MoC proposals in preparation or pending approval 6. MoC: numbers of E/C&I MoC proposals pending implementation 7. MoC: numbers of MoC proposals awaiting close-out of commissioning test reservations

4.3 E/C&I Management of Change

Suitable arrangements and skills for Management of Change (MoC) are essential for managing ageing E/C&I equipment.

Solutions to E/C&I refurbishment projects or upgrades using purely analogue equipment are now extremely difficult, since new analogue equipment is becoming increasingly difficult to procure. Hence almost all new E/C&I equipment is digital or software-based.

In the recent past, there has been a record of some E/C&I projects (and in the wider sense, major IT projects in general) failing to achieve their objectives. Some of these failures have been due to the very complexity that software-based solutions make possible. Other failures have been due to the problems of safety justification of software-based systems.

Hence the replacement of ageing E/C&I equipment requires proper arrangements for MoC. Key elements of good practice for MoC, include:

1. High-level issues about the Company MoC capability.
2. Software maintenance and configuration management.
3. Project management issues.
4. Competency management for E/C&I maintenance, testing, modification, and refurbishment.

Key aspects are discussed further below.

4.3.1 Management of Change (MoC) Capability

In order to be able to replace ageing analogue equipment with digital equipment there is a need to have robust MoC arrangements in place in accordance with IEC 61508 (Functional Safety of electrical/electronic/programmable electronic safety-related systems) or IEC 61511 (Functional safety – Safety Instrumented systems for the process industry sector).

The main issues for MoC are:

1. Do staff have the necessary skills?
2. Does the MoC process cover the essential aspects of IEC61508/IEC 61511? These include:
    a. Functional Safety Management
    b. SIL requirements assessment
    c. Equipment SIL rating
    d. Software maintenance arrangements
    e. Software configuration management
3. Learning from the past

4.3.2 Software Maintenance and Configuration Management of Plant Computer Control Systems

Plant computer control systems such as DCS can be very large and complex, sometimes with millions of lines of code. Maintenance of these systems requires care, attention, effort and resources.

DCS should not be used for critical safety applications, but may have a role in providing enhanced alarm and diagnostic information which can aid safety and hence it is important to ensure that DCS work to a high level of reliability and availability, and that changes to them are effectively managed

A particular issue with older programmable DCS/SCADA systems may be the use of obsolete computer languages. The availability of programmers for old languages can be an issue.

Many of these issues may also apply to smaller software-based systems, e.g. discrete plant monitoring systems, some of which may be safety-related.

Alarm management systems, where used to prevent the operator seeing excessive numbers of alarms simultaneously, should be designed using best practice such as EEMUA 191 [25] and the Human Factors HSE Inspectors Toolkit [26].

Adequate controls should exist to ensure that DCS/SCADA software cannot suffer unplanned changes and interference. These controls may include firewalls and software MoC arrangements. General advice on data security issues in industry can be obtained from the following sources:

- HSE CRR/408, *Safety Implications of Industrial Uses of Internet Technology* [27]
- The Centre for the Protection of National Infrastructure (CPNI) publishes good practice guides on its website: http://www.cpni.gov.uk/ProtectingYourAssets/scada.aspx

4.3.3 Project Management Issues for Large E/C&I Refurbishment Projects

In the recent past, there has been a record of some E/C&I projects (and in the wider sense, major IT projects in general) failing to achieve their objectives. Some of these failures have been due to the very complexity that software-based solutions make possible. Other failures have been due to the problems of safety justification of software-based systems.

Sound project management arrangements can go a long way to help mitigate the risks of project failure. This issue was addressed in some detail in the Royal Academy of Engineering/British Computer Society (RAE/BCS) 2004 report *The Challenges of Complex IT Projects* [28].

The report also contains a succinct list of key issues for senior management for IT projects, most of which relates also to large E/C&I refurbishment projects on modern process plant.

5.0 Where to find out more

In addition to the specific references quoted in this report, the following sources provide further useful background on Ageing Plant.

5.1 Accident statistics and analysis

- Major Accident Reporting System (MARS)
- Major Hazard Incident Data Service (MHIDAS)
- A Review of High-Cost Chemical/Petrochemical Accidents Since Flixborough 1974, IchemE Loss Prevention Bulletin April 1998
- Loss Prevention Bulletin, various issues
- Hazardous Cargo Bulletin, various issues
- Large Property Damage Losses in the Hydrocarbon Chemical Industries – A Thirty Year Review, 2001
- The Costs of Accidents at Work, Health and Safety Executive, 1997
- 1999 Process Safety Performance Measurement Report, API
- Report on a Study of International Pipieline Accidents, Health and Safety Executive, CRR 294/2000

5.2 Ageing mechanisms and their management

- API RP 571, Damage Mechanisms Affecting Fixed Equipment in the Refining Industry
- API RP 574, Inspection Practices for Piping System Components
- RR 076, Machinery and Rotating Equipment Integrity Inspection Guidance Notes
- RR 253, Piping Systems Integrity, Management Review
- API Standard 1160, Managing System Integrity for Hazardous Liquid Pipelines.
- Corrosion, Shrier, Elsevier
- Fitness-for-Service and Integrity of Piping, Vessels and Tanks. ASME Code Simplified. G Antaki

5.3 Good practice guides

- PAS 55, Asset Management, The Institute of Asset Management
- Best Practice for Risk Based Inspection as a Part of Plant Integrity Management, CRR 363/2001

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1 Plant ageing, Management of equipment containing hazardous fluids or pressure, HSE Research Report RR509, HSE Books, 2006

2 Plant Ageing Study – Phase 1 Report, ESR/D0010909/003/Issue2, A Report prepared for the Health and Safety Executive, 27th February 2009

3 Energy Institute Document "Guidance for Corrosion Management in Oil and Gas Production and Processing"

4 NACE Corrosion Engineer's Reference Book, 3rd Edition

5 API 571, Damage Mechanisms Affecting Fixed Equipment in the Refining Industry

6 HSE Research Report 076, "Machinery and Rotating Equipment Integrity Inspection Guidance Notes"

7 API Recommended Practice 573, "Inspection of Fired Boilers and Heaters"

8 Concrete Repair According to the New European Standard EN 1504, Prof Dr Ing M Raupach, RWTH Aachen, ibac

9 EN 1504, "Products and systems for the protection and repair of concrete structures"

10 BS EN 12696:2000, "Cathodic Protection of Steel in Concrete"

11 ISO 14692-4:2000, "Petroleum and natural gas industries -- Glass-reinforced plastics (GRP) piping -- Part 4: Fabrication, installation and operation"

12 API RP 1632 (2002), "Cathodic Protection of Underground Petroleum Storage Tanks and Piping Systems"

13 HSG 254, Developing Process Safety Indicators, HSE Books

14 HID CI, SI Inspection Manual, issued 11/4/2001, HSE website

15 HSG 65, Successful Health and Safety Management, HSE Books

16 HSE Human Factors Briefing Note No. 2 – Competence, HSE website

17 HSE Technical Measures Document – Maintenance Procedures, HSE website

18 HSE Human Factors Briefing Note No. 11 – Organisational Change, HSE website

19 BS EN 61508:2002 Functional safety of electrical/electronic/programmable electronic safety-related systems

20 IEC 61511 Functional safety – Safety instrumented systems in the UK process industries

21 EEMUA 222:2009 Guide to the Application of IEC 61511 to safety instrumented systems in the UK process industries

22 E/C&I Plant Ageing: A Technical Guide for Specialists managing Ageing E/C&I Plant

23 AEA Technology, Developments in electrification systems – Life expectancy of electrical equipment, AEATR-EE-2005-030, June 2005

24 HSE CRR 428(2002), Principles for proof testing of safety instrumented systems in the chemical industry

25 EEMUA 191:2007 Alarm systems - a guide to design, management and procurement

26 Human Factors HSE Inspectors Toolkit, HSE web-site

27 HSE CRR/408(2002), Safety Implications of Industrial Uses of Internet Technology

28 The Challenges of Complex IT Projects, Royal Academy of Engineering/British Computer Society, 2004

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Plant Ageing Study

Phase 1 Report

Between 1996 and 2008 it is estimated that there have been 173 loss of containment incidents reported in RIDDOR that can be attributable to ageing plant. This represents 5.5% of all loss of containment events. The limited information provided in RIDDOR about the underlying causes means that it is difficult to identify which events may be age related: the actual number could be much higher than that quoted here.

Across Europe, between 1980 and 2006, it is estimated that there have been 96 incidents reported in the MARS database relating to major accident potential loss of containment which are estimated to be due to ageing plant. This represents 28% of all reported 'major accident' loss of containment events in the MARS database and equates to an overall loss of 11 lives ,183 injuries and over 170Million € of economic loss.

As the MARS data provides the more detailed and comprehensive insight into the incidents and causal factors and is specifically related to potential major accident hazard events, it is considered that this represents a more realistic indication of the extent and severity of ageing plant and its contribution to major accidents. This leads to the conclusion that ageing plant is a significant issue.

Onshore chemical plant in the UK is ageing. Health and Safety Executive (HSE) field inspectors often have to consider the Operators' safety justification for continued use of ageing plant taking account of a variety of issues such as usage, design life, known research, known operational and failure history, maintenance and inspection history, etc. The issues also need to be considered against a background of increasing competition from overseas, and the pressure on resources and investment which this has had over recent years, with reductions in manning levels, early retirement of experienced staff, and pressure on operating budgets.

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