Corrosion threats handbook
Upstream oil and gas production plant

in association with Oil & Gas UK

HSE Health & Safety Executive
Acknowledgements

The Institute wishes to record its appreciation of the work carried out by Dave Moore of Lloyd's Register EMEA for compiling this document and for input of expertise into its detail and content and members of the Corrosion Management Working Group who provided valuable expertise through meeting attendance and correspondence.

The origins of this document and further details of the Work Group can be found in the associated publication: Guidance for corrosion management in oil and gas production and processing which is referenced throughout this document.

Foreword

This publication was compiled to enhance the awareness of corrosion for a large cross section of personnel within the oil and gas industry. It was produced in parallel to the main guideline publication, Guidance for corrosion management in oil and gas production and processing which was prepared following consultation with a large cross section of UK offshore operators, specialist contractors and independent verification bodies who have a role in the control of corrosion.

This document is for guidance only, and while every reasonable care has been taken to ensure the accuracy and relevance of its contents, the Energy Institute, its sponsoring companies, the document writer and the Working Group members, shall not be liable to any person for any loss or damage which may arise from the use of any of the information contained in any of its publications.

This handbook may be reviewed from time to time and it would be of considerable assistance for any future revision if users would send comments or suggestions for improvements to:

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Introduction

Oil and gas production facilities must continue to strive for, and improve, safety, environmental, production and cost goals at a time when many UK plants are extending their period of operation beyond their original design life. Effective management of corrosion of the structures and systems is a core requirement to achieve those goals. The role of plant operation, maintenance, inspection and support personnel is, in turn, critical in maintaining the integrity of their plant. The Energy Institute has commissioned this guide as a concise reference tool to assist these individuals by providing practical information to illustrate the corrosion degradation mechanisms likely to affect upstream oil and gas production systems, structures and components. The guide outlines the causes of the corrosion threats, shows typical locations for their occurrence and gives examples of how the threats may be managed.

The guide is intended for use by plant engineers and personnel with direct and indirect responsibility for the long-term integrity of production facilities. It should assist system housekeeping and more formal integrity audits. The guide should also be of value to practitioners of Integrity Management, especially those less familiar with corrosion issues specific to oil and gas production plant.

The information should allow the user to:

- Understand the key corrosion threats (both internal and external corrosion)
- Understand the typical appearance of the main threats
- Understand where the threats may occur
- Identify the conditions which may give rise to threat
- Consider actions to mitigate the threat

The majority of the corrosion threats apply to carbon steel, the most commonly used material for upstream oil and gas production systems, structures and components. Threats to other materials are identified.

This guide has been prepared to supplement the Energy Institute publication *Guidance for corrosion management in oil and gas production and processing*. Where appropriate, reference has been made to the relevant sections of Appendix B of that document, where more detailed information on managing each of the corrosion threats can be found.

The information in this guide should NOT be used to the exclusion of established and applicable codes, standards and criteria; nor should the threats and their manifestation described in this guide be seen as exhaustive. Please notify and consult with the relevant technical engineering authority/discipline specialists for investigation of potential threats or actual degradation that may be observed.

The corrosion threats in this guide are presented either as specific corrosion mechanisms, e.g. microbial corrosion, erosion corrosion; or by location, e.g. external corrosion, corrosion under insulation. In addition to the threats which are strictly corrosion, three other degradation processes are included in this handbook. They are: erosion, fatigue and fretting. In practice, corrosion may be driven by two or more mechanisms. Typically, the resultant corrosion rate is faster than would be anticipated from a single mechanism.
Corrosion basics

The metal used to fabricate process plant and structures is a metastable material. Fundamental laws of thermodynamics tell us that metals we use have the innate potential to convert to a more stable (lower energy) form.

The rusting of steel is a well known example of the conversion of a metal (iron) into a more stable, lower energy state, non-metallic product (rust). The change in energy of the system is the driving force for this process. It is no coincidence that the corrosion products we observe on our facilities are the same compounds as the original ores from which the metals were extracted, for example, iron oxides, iron carbonates and iron sulphides.

Controlling corrosion

It follows therefore that, without our intervention, the metals from which facilities are fabricated will inevitably return to the non-metallic compounds from which they were extracted.

Recognising the indicators of degradation and understanding the causes, forms the basis of the process by which the threat of corrosion may be managed.

The fire triangle analogy

The majority of the corrosion reactions which occur in upstream production facilities are aqueous oxidation processes. As such they are analogous to combustion, another process by which a material is oxidised (by the oxygen in air) to a lower energy compound. The well known Fire Triangle has an aqueous corrosion equivalent, which may aid our understanding of corrosion and the methods used to mitigate corrosion.
The corrosion triangle
In the same way that a fuel requires oxygen and energy to combust, a metal requires water and a corrodent, for aqueous corrosion to occur.
The water required for corrosion to occur may be atmospheric moisture or sea / rain water (in the case of external corrosion), produced water (in the case of internal corrosion of hydrocarbon processing systems) or seawater (in the case of seawater injection systems).
The corrodents are typically:
- Oxygen - atmospheric corrosion of steel structures, internal corrosion of water systems
- Carbon dioxide – co-produced with oil and gas
- Hydrogen sulphide – produced from sour wells, or by microbial action in production plant or water systems
- Acids – either co-produced in production fluids, or those used for well stimulation, or acidic production chemicals

Corrosion control
The analogy with the fire triangle can be taken further in the context of corrosion mitigation. A fire can be controlled by removing any one of the three elements, e.g. a carbon dioxide blanket to prevent oxygen access, or cooling with water to reduce the energy. In the same way, corrosion may be controlled by removing any one of the metal, water or corrodent components. Typical examples of these are:
- Replacing steel with glass reinforced plastic pipework in seawater systems
- Keeping insulation dry to prevent corrosion under insulation
- Deaerating (removing oxygen from) seawater prior to downhole injection
- Coating to isolate a metal from water

The principle of removing at least one of the three necessary components for corrosion lies behind most of the activities we implement to control corrosion and is worth bearing in mind when considering corrosion issues and mitigation measures.
How to use this handbook

The typical process and utility systems in upstream oil and gas production facilities are illustrated in the simplified process flow diagrams that follow. Typical corrosion threats for each of the systems are listed on each of the diagrams. Each threat is numbered, so that the number can be used to refer to the description section of this guide. The description of each threat shows typical examples of degradation morphologies and provides information on: the causes of the threats; how the threat is manifested; which sections of the system are susceptible; typical monitoring and inspection methods; and how the threat may be managed.

More detailed information on these threats and their mitigation is given in the Energy Institute publication *Guidance for corrosion management in oil and gas production and processing*.

To differentiate between the main and less common threats to each section of the plant, the major threats are highlighted in red.

<table>
<thead>
<tr>
<th>Abbreviations</th>
</tr>
</thead>
<tbody>
<tr>
<td>The abbreviations used in the description section of the handbook are:</td>
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<tr>
<td>General abbreviations</td>
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<tr>
<td>CP</td>
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<td>EFC</td>
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<td>WP</td>
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<td>SCC</td>
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</table>
Degradation threats to the oil process and produced water systems

### Internal threats: topsides

**Water-wet hydrocarbon fluids**

- 
  - **CO₂** / **H₂S** / **O₂** / **MIC** / **Galv** / **Weld** / **Groove**
  - **Crev** / **SCC** / **Eros** / **Eros Corr** / **Ext Corr** / **Acid**

### External threats: topsides

- **Ext Corr** / **CUI** / **F&F**

### Internal threats: downhole

- **CO₂** / **H₂S** / **MIC** / **Galv** / **Weld** / **Groove** / **Crev**
  - **SCC** / **Eros** / **Eros Corr** / **Ext Corr** / **Acid**

### External threats: downhole

- **Ext Corr** / **F&F**

---

**Main threats are shown in red**

See Description section (pages 12-26) for information on the threats.
Degradation threats to the gas process system

**Wet gas**
- **Internal threats**
  - CO₂ / H₂S / O₂ / MIC / Galv / Crev / Eros Corr / Acid
- **Dry gas**
  - No internal threats

**Dry gas**
- **Internal threats**
  - CO₂ / H₂S / O₂ / MIC / Galv / Crev / Eros Corr / Acid
- **No internal threats**

**Total system**
- **External threats**
  - Ext Corr / CUI / F&F

---

**Note:**
1, 2 or 3 stages of compression prior to dehydration

---

**Wet gas**
- **Internal threats**
  - CO₂ / H₂S / O₂ / MIC / Galv / Crev / Eros Corr / Acid

**Dry gas**
- **Internal threats**
  - CO₂ / H₂S / O₂ / MIC / Galv / Crev / Acid

**Main threats shown in red**

See Description section (pages 12-26) for information on the threats.

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**Table of Threats and Abbreviations**

<table>
<thead>
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<th>#</th>
<th>Threat</th>
<th>Abbr’n</th>
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<tbody>
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<td>Carbon Dioxide Corrosion</td>
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<td>F&amp;F</td>
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<td>LME</td>
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<tr>
<td>14b</td>
<td>Misc. – Acid Corrosion</td>
<td>Acid</td>
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Degradation threats to the seawater system

**Internal threats**
- O₂ / MIC / Galv / Weld / Groove / Crev / Eros Corr

**External threats**
- Ext Corr / CUI / F&F

### Corrosion threats

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Main threats are shown in red

See Description section (pages 12-26) for information on the threats.
Degradation threats to the cooling and heating medium systems

**Cooling medium system**

**Internal threats**
- O₂ / MIC / Galv / Weld / Crev

**External threats**
- Ext Corr / CUI / F&F

**Internal threats**
- Recirc pumps
- Eros Corr

**Heating medium system**

**Internal threats**
- O₂ / MIC / Galv / Weld / Crev

**External threats**
- Ext Corr / CUI / F&F

**Internal threats**
- Recirc pumps
- Eros Corr

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### Table: Corrosion Threats

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See Description section (pages 12-26) for information on the threats.
Degradation threats to the diesel and drainage systems

**Diesel system**

**Internal threats**
- O₂ / MIC / Weld / Crev

**External threats**
- CO₂ / O₂ / MIC / Weld / Crev

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<td>Acid</td>
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</tbody>
</table>

**Closed drains system**

**Internal threats**
- CO₂ / O₂ / MIC / Weld / Crev

**External threats**
- Ext Corr / CUI / F&F

**External Corrosion Ext Corr**

**Corrosion under Insulation CUI**

**Stress Corrosion Cracking SCC**

**Fatigue and Fretting F&F**

**Misc. – Liquid Metal Embrittlement LME**

**Misc. – Acid Corrosion Acid**

**Safe open drains system**

**Hazardous open drains system**

**Main threats are shown in red**

See Description section (pages 12-26) for information on the threats.
### THREAT #1 – CARBON DIOXIDE (CO₂) CORROSION

<table>
<thead>
<tr>
<th>CAUSES</th>
<th>OCCURRENCE</th>
<th>SUSCEPTIBLE SYSTEMS</th>
<th>INSPECTION / MONITORING METHODS</th>
<th>MANAGEMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>– Dissolved carbon dioxide, produces carbonic acid</td>
<td>– All water-wetted locations in hydrocarbon systems</td>
<td>– All (water containing) hydrocarbon processing systems</td>
<td>– Process parameter monitoring, e.g. temperature, pressure, dew point</td>
<td>– Corrosion resistant alloy</td>
</tr>
<tr>
<td>– Inadequate corrosion inhibition</td>
<td>– Pipework straights (6 o’clock)/bends/tees/reducers</td>
<td></td>
<td>– UT</td>
<td>– Chemical inhibition</td>
</tr>
</tbody>
</table>

### DEGRADATION MORPHOLOGY

- General corrosion (flow influenced)
- Localised corrosion (low flow)
- Preferential weld corrosion
# Threat #2 - Hydrogen Sulphide (H₂S) Corrosion

<table>
<thead>
<tr>
<th>Causes</th>
<th>Occurrence</th>
<th>Susceptible Systems</th>
<th>Inspection / Monitoring Methods</th>
<th>Management</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Hydrogen sulphide and water</td>
<td>- Pitting – typically at 6 o’clock</td>
<td>- All water-wetted locations in sour hydrocarbon service</td>
<td>- Process parameter monitoring, e.g. temperature, pressure, dew point</td>
<td>- Materials to ISO15156</td>
</tr>
<tr>
<td></td>
<td>- Stress cracking - (Sulphide Stress and Hydrogen Induced Cracking) especially at locations of high stress, applied or residual, e.g. welds, bends, welded on trunnions</td>
<td>- Susceptible materials (i.e. not meeting ISO 15156 criteria)</td>
<td>- UT</td>
<td>- Chemical inhibition/ H₂S scavenging</td>
</tr>
<tr>
<td></td>
<td>- Blistering of carbon steel pipework and vessels</td>
<td></td>
<td>- Radiography</td>
<td>- Avoid rolled plate product</td>
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<td></td>
<td></td>
<td></td>
<td>- Dye penetrant inspection (cracking)</td>
<td>- Keep dry (internally)</td>
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<td></td>
<td></td>
<td></td>
<td>- Eddy current inspection (cracking)</td>
<td>- See EI Guidance document Appdx B, Section 2</td>
</tr>
</tbody>
</table>

## Degradation Morphology

- Localised corrosion
- Sulphide stress cracking - Branched cracking
- Hydrogen blistering
## THREAT #3 - OXYGEN (O₂) CORROSION

<table>
<thead>
<tr>
<th>CAUSES</th>
<th>OCCURRENCE</th>
<th>SUSCEPTIBLE SYSTEMS</th>
<th>INSPECTION / MONITORING METHODS</th>
<th>MANAGEMENT</th>
</tr>
</thead>
</table>
| – Oxygen in an aqueous phase  
– Oxygen ingress e.g. at leaks  
– Under dosing oxyscavenger  
– Inadequate performance of mechanical deaeration (Water injection systems) | – All aerated water-wetted locations  
– Pipework – straights, bends, welds  
– Vessels  
– Exacerbated by deposits (under deposit corrosion) | – Water injection: pipework, vessels, pumps and flowlines  
– Seawater system  
– Firewater system  
– Open drains  
– Heating and cooling medium | – Process parameter monitoring, e.g. oxygen scavenger residual, flow rate  
– UT  
– Radiography  
– Corrosion probes / coupons | – Oxygen removal (Deaeration, oxygen scavenging)  
– Leak prevention (avoid oxygen ingress)  
– Monitor oxygen  
– See EI Guidance document Appdx B, Sections 3, 6 and 7 |

### DEGRADATION MORPHOLOGY

- General oxygen corrosion
- Oxygen corrosion at welds
- Oxygen corrosion at the inlet of a deaerator tower
### Threat #4 – Microbiologically Influenced Corrosion (MIC) and Deadleg Corrosion

<table>
<thead>
<tr>
<th>Causes</th>
<th>Occurrence</th>
<th>Susceptible Systems</th>
<th>Inspection / Monitoring Methods</th>
<th>Management</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primarily sulphate reducing bacteria</td>
<td>Water containing organic nutrient and sulphate</td>
<td>Water injection</td>
<td>Microbial and sulphide sampling and trending</td>
<td>Biocide</td>
</tr>
<tr>
<td>Stagnant (deoxygenated) environments</td>
<td>Deadlegs – permanent or operational</td>
<td>Produced water treatment and re-injection</td>
<td>UT</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mothballed plant</td>
<td>Firewater</td>
<td>Radiography</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Under deposits</td>
<td>Drains</td>
<td>Biostuds / sidestream monitoring</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Seawater</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Occasionally in – hydrocarbon processing systems, e.g. vessel trim, recovered oil lines</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Degradation Morphology

- MIC pits in carbon steel
- MIC in a carbon steel deadleg
- Microbially initiated erosion corrosion of Cunifer (90/10 copper-nickel)
# Threat #5 – Galvanic Corrosion

<table>
<thead>
<tr>
<th>Causes</th>
<th>Occurrence</th>
<th>Susceptible Systems</th>
<th>Inspection / Monitoring Methods</th>
<th>Management</th>
</tr>
</thead>
</table>
| – Dissimilar metals in a corrosive electrolyte  
– Incorrect weld metallurgy  
– Defects in noble metal coatings | – All plant, especially at:  
– Welds  
– Screwed fittings (small anode / large cathode combination)  
– Some types of gasket  
– Noble metallic coatings, e.g. nickel plated carbon steel  
– Dissimilar metals in pumps | – Seawater systems are particularly susceptible  
– Water injection  
– Hydrocarbon systems  
– Drains  
– Electroless nickel plated pipework and vessels  
– Corrosion resistant alloy clad carbon steel vessels  
– Under insulation | – UT  
– Radiography | – Materials selection  
– Weld consumable selection/weld procedures  
– Gasket selection  
– Use insulating gasket sets/insulating spool (where appropriate)  
– Sacrificial spool / coat cathode / CP  
– See EI Guidance document Appdx B, Section 5 |

## Degradation Morphology

- Galvanic corrosion of carbon steel in contact with Cunifer
- Galvanic corrosion of cupro-nickel in a firewater system which incorporated both CuNi and duplex stainless steel spools
- Galvanic corrosion of nickel plated carbon steel

**Inspection / Monitoring Methods**

- Ultrasonic testing (UT)
- Radiography
## Threat #6 – Weld Corrosion

<table>
<thead>
<tr>
<th>Causes</th>
<th>Occurrence</th>
<th>Susceptible Systems</th>
<th>Inspection / Monitoring Methods</th>
<th>Management</th>
</tr>
</thead>
</table>
| – Microstructural and/or compositional difference between the weld and its parent metal, resulting in a galvanic effect.  
– Poor weld quality  
– Poor weld morphology, e.g. weld root protruding out | – Pipelines/flowlines  
– Pipework | – All systems where CO₂ O₂ and erosion corrosion occurs.  
– Systems subjected to acetic acid injection | – UT  
– Radiography  
– On-line monitoring, e.g. using welded probes | – Weld consumable selection  
– Control welding quality  
– Use of corrosion inhibitor  
– See EI Guidance document Appdx B, Section 6 |

### Degradation Morphology

- Corrosion at weld heat affected zone
- Weld corrosion
- Corrosion at weld heat affected zone
## THREAT #7 - GROOVING CORROSION

<table>
<thead>
<tr>
<th>CAUSES</th>
<th>OCCURRENCE</th>
<th>SUSCEPTIBLE SYSTEMS</th>
<th>INSPECTION / MONITORING METHODS</th>
<th>MANAGEMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>– Synergy of two or more corrosion mechanisms, i.e. erosion, oxygen, carbon dioxide, microbial and H₂S corrosion</td>
<td>– Centred on the 6 o’clock position of horizontal / near horizontal pipelines</td>
<td>– Water injection pipework and pipelines - Production fluid pipework and pipelines.</td>
<td>– Monitor parameters influencing primary mechanisms - Intelligent pigging</td>
<td>– Mitigate primary mechanisms (CO₂, O₂, MIC, erosion) - Materials selection - See EI Guidance document Appdx B, Section 3</td>
</tr>
</tbody>
</table>

### DEGRADATION MORPHOLOGY

- Grooving corrosion of a water injection pipeline
- Grooving corrosion of a water injection pipeline
- Grooving corrosion of a water injection pipeline
## THREAT #8 – CREVICE CORROSION AND FLANGE FACE CORROSION

<table>
<thead>
<tr>
<th>CAUSES</th>
<th>OCCURRENCE</th>
<th>SUSCEPTIBLE SYSTEMS</th>
<th>INSPECTION / MONITORING METHODS</th>
<th>MANAGEMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>– Differential concentration cell</td>
<td>– Flange/gasket interfaces</td>
<td>– All systems, carbon steel and stainless steel. Especially seawater systems (oxygen containing)</td>
<td>– Difficult for flanges</td>
<td>– Materials selection, e.g. gaskets, instrument tubing materials</td>
</tr>
<tr>
<td></td>
<td>– Under clamps on instrument tubing</td>
<td></td>
<td>– Visual inspection, especially during maintenance</td>
<td>– Weld overlay flange faces with corrosion resistant alloy</td>
</tr>
<tr>
<td></td>
<td>– Bolt/flange interfaces</td>
<td></td>
<td></td>
<td>– Temporary preservatives (wax, grease) on fasteners and tube clamps</td>
</tr>
</tbody>
</table>

### DEGRADATION MORPHOLOGY

- Crevice corrosion of a flange/gasket interface
- Crevice corrosion of instrument tubing under clamps
- Crevice corrosion of bolting

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## THREAT #9 – EXTERNAL CORROSION: (A) COATINGS, (B) FASTENERS AND (C) SUBSEA

<table>
<thead>
<tr>
<th>CAUSES</th>
<th>OCCURRENCE</th>
<th>SUSCEPTIBLE SYSTEMS</th>
<th>INSPECTION / MONITORING METHODS</th>
<th>MANAGEMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coatings degradation/damage (e.g. lack of fabric maintenance)</td>
<td>Field applied coatings especially susceptible to degradation</td>
<td>Visual inspection</td>
<td>Fabric maintenance</td>
</tr>
<tr>
<td></td>
<td>Inadequate surface preparation prior to coating</td>
<td>Carbon steel bolting / fasteners</td>
<td>Subsea - video inspection by ROV</td>
<td>Materials selection, e.g. galvanised bolting</td>
</tr>
<tr>
<td></td>
<td>Deposit build-up on pipework / vessels</td>
<td>Pitting corrosion of stainless steel</td>
<td>Bolting and fittings</td>
<td>Coat hot stainless steels</td>
</tr>
<tr>
<td></td>
<td>Incorrect materials selection, e.g. carbon steel bolting on stainless flanges</td>
<td>Stress corrosion cracking of stainless steel</td>
<td>Gratings and walkways</td>
<td>Avoid deposit build-up</td>
</tr>
<tr>
<td></td>
<td>Inadequate cathodic protection (Subsea)</td>
<td>All coated topsides pipework, vessels</td>
<td>Subsea structures and components</td>
<td>Cathodic protection (Subsea)</td>
</tr>
</tbody>
</table>

### DEGRADATION MORPHOLOGY

- Coating degradation
- Corroded bolting, e.g. carbon steel bolting in stainless steel equipment
- Deposit build-up leading to under-deposit corrosion

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### Threat #10 – Corrosion Under Insulation

<table>
<thead>
<tr>
<th>Causes</th>
<th>Occurrence</th>
<th>Susceptible Systems</th>
<th>Inspection / Monitoring Methods</th>
<th>Management</th>
</tr>
</thead>
</table>
| – Wet insulation  
– Damaged or missing Cladding  
– Degraded seals on sheet metal cladding  
– Missing or damaged coating | – CUI tends to be at 6 o’clock location on pipework / vessels / attachments; but can occur at any orientation  
– Higher probability and rate of corrosion on warm / hot pipework (40°C to 80°C for carbon steel)  
– Chloride pitting and cracking of stainless steels | – Insulated pipework and vessels across all systems  
– Heat traced components | – Visual inspection  
– Strip and search  
– Real time radiography  
– Thermography for wet insulation  
– Pulsed eddy current | – Avoid insulation where possible  
– Effective coatings and maintenance of coatings  
– Fabric maintenance  
– RBI  
– See EI Guidance document Appdx B, Sections 10 and 14  
– See also: EFC WP15 Corrosion Under Insulation Guidelines |

#### Degradation Morphology

- Corrosion under insulation (carbon steel pipework)
- Damaged cladding
- CUI with telltale staining (Vessel 6 o’clock location)
## THREAT #11 – STRESS CORROSION CRACKING (SCC)

<table>
<thead>
<tr>
<th>CAUSES</th>
<th>OCCURRENCE</th>
<th>SUSCEPTIBLE SYSTEMS</th>
<th>INSPECTION / MONITORING METHODS</th>
<th>MANAGEMENT</th>
</tr>
</thead>
</table>
| – Chlorides in oxygenated environment acting on susceptible materials  
– May occur as an internal mechanism in absence of oxygen at high chloride levels and high temperature  
– Impact of CP of duplex SS subsea (Hydrogen Induced Stress Cracking)  
– Dry methanol (titanium)  
– Amines (carbon steel in scrubbing systems) | – Internally and externally  
– Stainless steel (SCC)  
– Duplex stainless steel  
– High strength carbon steel  
– Especially areas of stress concentration, e.g. welds or high residual stress | – Hot topsides stainless steel pipework and vessels  
– Subsea cathodically protected duplex stainless steel, e.g. manifolds, pipelines  
– Overprotected (CP) high strength carbon steel (Subsea) | – Process parameter monitoring, e.g. temperature, chloride concentration  
– Eddy current  
– Dye penetrant  
– UT  
– Radiography  
– Visual | – Paint/thermally sprayed aluminium  
– Materials selection  
– Follow weld procedures and QC  
– Temperature control  
– CP design (subsea)  
– Diode control of CP  
– See EI Guidance document Appdx B, Section 11 |

### DEGRADATION MORPHOLOGY

- External SCC of a duplex SS vessel
- SCC of a 316L SS pipework
## THREAT #12a - EROSION

<table>
<thead>
<tr>
<th>CAUSES</th>
<th>OCCURRENCE</th>
<th>SUSCEPTIBLE SYSTEMS</th>
<th>INSPECTION / MONITORING METHODS</th>
<th>MANAGEMENT</th>
</tr>
</thead>
</table>
| – High fluid flow rates  
– Sand/solids/proppant  
– Sand washing (e.g. separators) | – Solids-containing fluids  
– Pipework – straights, bends, welds  
– Vessels  
– Valves  
– Flow obstructions, e.g. thermowells | – Any system exposed to sand / solids production, especially:  
- Risers,  
- Valves,  
- 1st stage, test/ clean-up separators  
- Produced water system | – Monitor process parameters, e.g. flow rate, solids prod’n rate  
– UT  
– Radiography  
– Acoustic probes  
– Intrusive erosion probes  
– Corrosion resistant coupons | – Flow control  
– Sand management  
– Well management  
– Erosion resistant materials, facings and coatings  
– Increase pipe diameter and/or bend radius  
– See EI Guidance document Appdx B, Section 12 |

### DEGRADATION MORPHOLOGY

- Orifice plate erosion – High flow rates and solids
- Erosion at a bend
- Eroded valve cage

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## THREAT #12b - EROSION (flow affected) CORROSION

<table>
<thead>
<tr>
<th>CAUSES</th>
<th>OCCURRENCE</th>
<th>SUSCEPTIBLE SYSTEMS</th>
<th>INSPECTION / MONITORING METHODS</th>
<th>MANAGEMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>– Combination of flow and corrodent (e.g. carbon dioxide or oxygen)</td>
<td>– All water-wetted locations</td>
<td>– All systems especially: - Three phase systems - Produced water - Seawater / water injection</td>
<td>– Monitor process parameters, e.g. factors affecting primary mechanisms, flow rate - UT - Radiography - Corrosion monitoring</td>
<td>– Flow control – Sand management – Well management – Erosion resistant materials, facings and coatings – Increase pipe diameter and/or bend radius – See EI Guidance document Appdx B, Section12</td>
</tr>
<tr>
<td></td>
<td>– Especially locations of flow disruption / acceleration</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>– Pipework – straights, bends, tees, welds, valves, downstream of pumps</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>– Vessels, especially nozzles, areas of impingement</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Degradation Morphology

- Erosion corrosion of carbon steel
- Erosion corrosion of cunifer (Copper-nickel alloy)
- Erosion corrosion of stainless steel
## THREAT #13 – FATIGUE AND FRETTING

<table>
<thead>
<tr>
<th>CAUSES</th>
<th>OCCURRENCE</th>
<th>SUSCEPTIBLE SYSTEMS</th>
<th>INSPECTION / MONITORING METHODS</th>
<th>MANAGEMENT</th>
</tr>
</thead>
</table>
| – Inadequately supported pipework  
– Slug flow in pipework or vessels  
– Strong vibration sources, e.g. reciprocating compressors  
– Flexing of structures, e.g. FPSO tanks and deck supports  
– Acoustic resonance in gas systems  
– Inadequate chemical injection quill design  
– Thermal cycling | – Small bore pipework (Fatigue)  
– CRA pipework (tends to be thinner wall than carbon steel) – (Fatigue)  
– Fretting, e.g. pipe supports, deck /wall penetrations, heat exchanger pipe supports/baffles | – All systems, especially at:  
- Pipe supports  
- Through wall penetrations  
- Heat exchangers, baffles / tube supports | – Visual inspection  
– Radiography  
– Vibration monitoring | – Stress analysis  
– Review and modify supports  
– Hydrodynamic modelling  
– Risk based inspection  
– Vibration monitoring  
– Adhere to Energy Institute Avoidance of vibration induced fatigue failure guidelines |

### DEGRADATION MORPHOLOGY

- **Fatigue crack of structural web**
- **Fretting pipework at a deck penetration**
- **Fatigue fracture of small bore tubing**
## Threat #14 – Miscellaneous: (a) Acid Corrosion (b) Embrittlement

<table>
<thead>
<tr>
<th>Causes</th>
<th>Occurrence</th>
<th>Susceptible Systems</th>
<th>Inspection / Monitoring Methods</th>
<th>Management</th>
</tr>
</thead>
</table>
| - Co-produced organic acids, e.g. acetic acid  
- Glycol decomposition products  
- Well acidisation and returns  
- Acidic production chemicals, e.g. scale inhibitor, acetic acid, oxygen scavenger  
- Co-produced mercury (Liquid Metal Embrittlement (LME)) | Acidic Corrosion  
- All water-wetted locations  
- Pipework straights (6 o’clock)/bends/tees/reducers  
- Welds, HAZ and downstream welds  
- Liquid Metal Embrittlement  
- Copper alloys in the presence of co-produced mercury.  
- Aluminium in the presence of co-produced mercury | Acidic corrosion  
- Hydrocarbon production systems, including gas systems, glycol regen., PW system  
- Liquid Metal Embrittlement  
- Hydrocarbon production systems, including gas systems | Acidic corrosion  
- UT  
- Radiography  
- Corrosion probes/coupons  
- LME  
- Dye penetrant/MP | Acidic corrosion  
- Corrosion resistant alloy  
- Chemical inhibition  
- LME  
- Remove mercury  
- Materials’ selection  
- Production chemical corrosion  
- Correct use of injection quills  
- Switch off injection while plant is not in use |

**Degradation Morphology**

- Corrosion by acidic production chemical (Scale inhibitor)
- Corrosion caused by acetic acid used to treat high naphthenic acid crude oil
- LME of brass (Tungum) tubing by mercury
This publication has been produced as a result of work carried out within the Technical Team of the Energy Institute (EI), funded by the EI's Technical Partners. The EI’s Technical Work Programme provides industry with cost effective, value adding knowledge on key current and future issues affecting those operating in the energy sector, both in the UK and beyond.