or regular application of batch biocide treatment. Continuous chlorination of the raw seawater systems means that stagnant zones and operational dead legs in the seawater systems should be flushed regularly, e.g. firewater ring mains.

In plant with seawater injection systems, consideration should be given to flushing dead legs during the regular batch biocide treatment of the system.

Although biocide treatment of production and drains systems is less common, it can be employed when microbial growth has become established.

If plant is isolated or mothballed, even temporarily, it is important to ensure that it is actually mothballed and that an appropriate mothballing procedure is applied, e.g. draining/flushing/drying or chemical treatment.

Chemical treatment is generally ineffective if deposits are present. These can shield areas of bacterial activity, and restrict CI access to the metal; solids removal is therefore essential prior to chemical treatment.

Chemical treatment target levels and flushing requirements should be reviewed on a regular basis and modifications made if required.

- Inspection of dead legs:

  Unless dead legs can be removed they must be inspected at a prescribed interval identified during the risk assessment process.

  The management of dead legs should be incorporated within the routine inspection plans of the facility. Inspection frequency must take account of the pipe wall thickness and expected deterioration rates (e.g. thin walled pipework may need more frequent inspection).

  Inspections should be targeted at locations where water and deposits can collect allowing microbial activity to develop. This is dependent upon the orientation and configuration of the pipework:

  These locations include:

  - Bottom third of any horizontal piping between the 4 and 8 o'clock position.
  - Off-takes originating from the lower half of horizontal lines; inspection will be targeted at low spots, bottom of vertical sections, horizontal sections, above closed valves etc.
  - Sections of off-takes close to the main line which are the source of bacteria, nutrients and heat.
  - Lowest parts of vessel bridle work, together with any associated level gauges.
  - Upstream of concentric reducers.
  - Locations where previous corrosion or erosion has reduced the wall thickness.
  - In multiphase line areas where condensation may occur.

Activity for the management of dead leg corrosion should be included in CMS audits.

I.6.4 CHECK

I.6.4.1 Measuring performance

The following are considered as proactive (leading) performance indicators:

- biocide injection against targets;
- CI injection against targets;
- flushing routines against targets;
- fluid sampling for microbial activity against targets;
- fluid sampling for CI levels against targets;
- bioprobe or coupon sampling for microbial activity against targets (where these exist);

- fluids sampling for solids content, and
- completion of inspection and corrosion monitoring activities to plan.

In addition, any change in the status of dead legs should be used to help understand whether the MIC threat has increased or decreased.

The following can be used as reactive (lagging) indicators:

- dead leg related failures;
- MIC damage in vessels, storage and ballast tanks;
- wall thickness loss in dead legs, against corrosion allowance, and
- corrosion rate in dead legs < (corrosion allowance/design life).

The dataset identified under leading performance indicators will provide assistance to the corrosion engineer in understanding whether the MIC threat associated with dead legs is under control.

I.6.4.2 Investigating accidents/incidents/near misses

Investigate the causes of dead leg corrosion-related incidents and accidents in order to reduce the likelihood of reoccurrence.

The investigation will be in accordance with the CM strategic plan which may be part of a wider integrity management plan.

The root cause of dead leg corrosion may be due to the primary factor, i.e. failure of treatments to control or it may be due to secondary factors such as accumulation of deposits, which make chemical treatments more difficult.

I.6.5 ACT

I.6.5.1 Reviewing performance

Performance review should include the following:

- Annual reviews of dead leg corrosion mitigation, monitoring and inspection outcomes. Corrective action for these programmes if indicated.
- Review of performance measures where applicable, in particular the assessment of reactive indicators and the overall trends in proactive indicators. Corrective action in strategy, organisation and planning if indicated.
- RCA of dead leg corrosion failures or management system failures with appropriate corrective action recommendation.
- Capture and roll-out lessons learned.

I.6.5.2 Learning lessons

The outcome of the performance review should be considered together with verification findings for offshore installations and audit results. Corrective action should be included in the strategy if indicated.

I.7 GALVANIC CORROSION

I.7.1 Introduction

Galvanic corrosion can occur at the junction of dissimilar metals coupled together in a suitable electrolyte, typically an aqueous environment or a wet atmosphere where oxygen is present.

The more noble metal (cathode) is protected by sacrificial corrosion of the less noble metal (anode). The anode corrodes at a higher rate than it would if it were not connected to the cathode. The relative exposed surface areas of the anode and cathode also have a significant effect – the corrosion rate of the anode can be high if there is a small anode-to-cathode ratio.

Internal galvanic corrosion is a particular concern in aerated seawater systems which are particularly susceptible due to high levels of oxygen, chlorine and iron in the water. Production systems exposed to a water phase may be less susceptible due to the absence of oxygen and if the production water has lower conductivity than seawater. Dry gas systems are less susceptible due to the lower proportion of water present and generally low conductivity of any electrolyte present.

External corrosion is exacerbated in bimetallic couples, for example, dissimilar metals flange connections, CS bolts in stainless steel or CRA flanges. The severity of the environment depends upon climatic conditions; it is low in dry or low-humidity regions, moderate in temperate and semi-arctic regions and in open rural locations, and high in regions with high humidity such as tropical and marine locations and also in polluted industrial atmospheres.

The following conditions are required for galvanic corrosion to occur:

- An electrolyte bridging the two metals – which may not necessarily be aggressive towards the individual metals when they are not coupled
- Electrical connection between the two dissimilar metals when there is physical contact or electrical continuity exists between the two
- A potential difference between the two metals of sufficient magnitude to provide a significant galvanic current
- A sustained cathodic reaction on the more noble metal in the couple by either the reduction of dissolved oxygen, hydrogen ions or other species that may be present in deaerated environments

In addition to the factors mentioned, others will need to be taken into account:

- resistance to ionic current flow of the electrolyte.
- resistance to current flow (by electron conduction) in the conducting materials and the quality of the connection between them, and
- the polarisation resistance of both the anode and the cathode.

The severity of galvanic corrosion when two dissimilar metals are in contact will depend upon the following factors:

- Electrode potential.
  The potential of any alloy, even in seawater, can be changed by a variety of factors such as temperature, velocity, chemical treatment etc. However, the relative ranking of alloys usually remains unchanged by these factors.
- Electrode polarisation.
  Depending on the particular metals and the environment, electrode polarisation is

the magnitude of the shift in the potential of the anode to a more electropositive value and the cathode to a more electronegative value.

- Variable potential.
  The corrosion potential of an individual metal can change and, in certain circumstances, the polarity of the galvanic couple can change. This is mainly affected by changes in pH, temperature and whether oxygen is present.
- Environment.
  Factors relating to the electrolyte (water) such as pH, chemical composition, conductivity and the dissolved oxygen content will affect galvanic couples.
- Area ratio.
  The corrosion rate of an anode will be higher when coupled to a cathode with a relatively larger surface area.
- Aeration and flow rate.
  In aerobic aqueous solutions where the cathodic reaction is controlled by the reduction of dissolved oxygen, the reaction rate will depend on the rate of diffusion of oxygen from the bulk solution to the metal surface. Therefore, both the reactant concentration and flow rate (transport to the surface) will affect severity and extent of bimetallic corrosion in the same way as single metal corrosion.
- Metallurgy.
  Differences in specific mechanical properties between nominally similar coupled metals or alloys can arise from cold working and heat treatment, for example, resulting in galvanic behaviour.
  In weldments, local changes in chemical composition at the weld bead and the heat affected zone of the parent metal can lead to galvanic corrosion. The specific issues relating to weldments are described further in Annex I.8.
  Alloys of a common type can have differing composition; thus 90/10 cupronickel can be anodic to 70/30 alloy and austenitic stainless steels are cathodic to the martensitic stainless steels.
- Exposure time.
  The corrosion rate of both coupled and non-coupled metals/alloys generally decreases with exposure time due to:
  - a reduction in oxygen diffusion through both electrolyte and any corrosion product present thus limiting the cathodic reaction;
  - the corrosion product protecting anodic areas on the metal surface, and
  - the development of magnesium and calcium containing calcareous deposits on the surface of the metal may offer a degree of corrosion protection thus decreasing the rate of galvanic corrosion.

  In contrast, where corrosion products are water-permeable, the rate of galvanic corrosion can increase because wet conditions are maintained at the surface and can be more aggressive than the bulk environment.
  The development and permeability of corrosion products on the surface of dissimilar metals in contact can lead to a reduction in coupled corrosion rate over time.

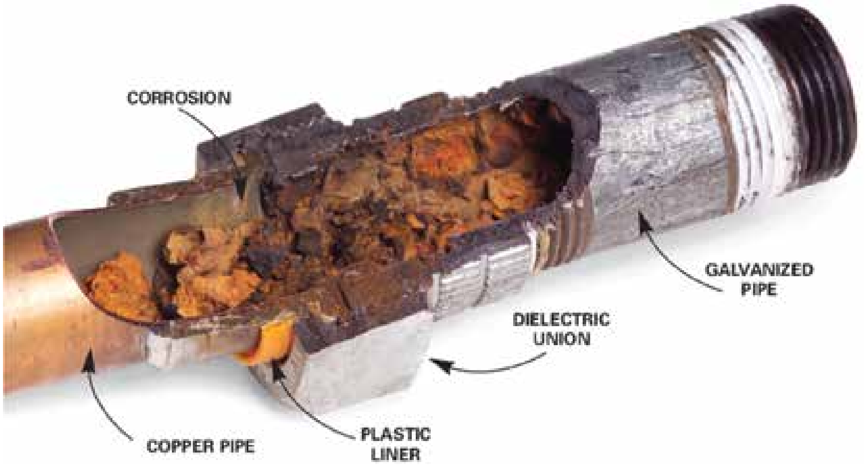
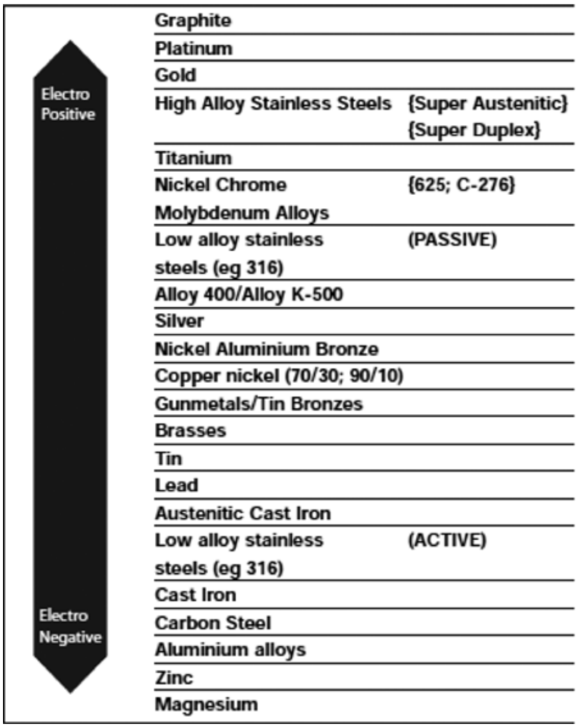


Figure I.19: Galvanic corrosion between a copper and carbon steel galvanised pipe connected by a dielectric union



Graphite	
Platinum	
Gold	
High Alloy Stainless Steels	{Super Austenitic} {Super Duplex}
Titanium	
Nickel Chrome Molybdenum Alloys	{625; C-276}
Low alloy stainless steels (eg 316)	(PASSIVE)
Alloy 400/Alloy K-500	
Silver	
Nickel Aluminium Bronze	
Copper nickel (70/30; 90/10)	
Gunmetals/Tin Bronzes	
Brasses	
Tin	
Lead	
Austenitic Cast Iron	
Low alloy stainless steels (eg 316)	(ACTIVE)
Cast Iron	
Carbon Steel	
Aluminium alloys	
Zinc	
Magnesium	

Figure I.20: Simplified Galvanic series in seawater (Guides to Good Practice in Corrosion Control – Bimetallic Corrosion; The National Physical Laboratory, DTI Publication, 1982)

Although the magnitude of the potential difference alone is not enough to determine the probability of galvanic corrosion to occur, as a rule of thumb, the galvanic potential difference between two dissimilar metals in contact, in a severe environment such as offshore/marine, should not exceed 0,15 V. For a normal ambient environment such as a storage warehouse or an uncontrolled temperature and humidity environment, a 0,25 V potential difference is acceptable. For a controlled environment, a 0,5 V potential difference can be tolerated. Nonetheless, there are other factors to be considered, such as those described here.

Most seawater resistant grades of stainless steels and Ni-Cr-Mo alloys can be considered compatible with each other but any of them will promote galvanic corrosion on less noble alloys such as cupro-nickel and monel; all CRAs will promote corrosion of CS.

Connection of CS to titanium alloys should also be avoided where a risk of galvanic corrosion or hydrogen charging of the titanium alloy may occur e.g. titanium alloy heat exchangers (tubes and tubesheets) combined with coated CS (e.g. a water box). Any holidays or defects in coatings on CSs will result in very high penetration rates of the steel.

At galvanic connections between dissimilar metals without electrical insulation or distance spool, it can be assumed that the local corrosion rate near the interface will be ~ three times higher than the average corrosion rate, decreasing exponentially away from the interface within a length of five pipe diameters. Particular systems may have higher corrosion rates depending on area ratio and material combinations.[37]

I.7.2 PLAN

I.7.2.1 Policy

Safety, environmental and commercial policies influence the choice of strategies for mitigation and monitoring/inspection.

The mitigation strategy options include:

- The primary mitigation for the threat of galvanic corrosion is in appropriate materials selection. The original design should identify and eliminate any potential threats.
- Avoiding small anode/large cathode dissimilar metal couples.
- Electrical isolation of dissimilar metals.
- Installation of an internal CP system e.g. resistor-controlled CP (RCP).
- Installation of a distance spool between the dissimilar metals to separate them by a minimum of 10–20 pipe diameters, depending on the guidance used. Distance spool may either be a solid non-conducting material e.g. GRP, or a metal that is coated internally with an electrically non-conducting material e.g. rubber. The coating should be applied to the more noble metal of the bimetallic couple.
- Application of a non-conducting internal coating on the more noble material in the vicinity of the bimetallic contact. The coating shall extend at least 10–20 pipe diameters into the more noble pipe material.
- Apply corrosion allowance (at design) to the less noble metal (hydrocarbon systems).

Monitoring/inspection strategy can include:

- Galvanic couples without any of the mitigating options identified in the previous paragraph can result in localised corrosion rates of *three times* the average corrosion rate. This should be considered when planning change-out of materials.
- Corrosion monitoring, although possible, is not practical; change-out of material or implementation of the strategies outlined previously should be pursued.

- Visual inspection and UT can be used to detect galvanic corrosion e.g. incorrect bolt specification in flange.

I.7.2.2 Planning

The CMS plan may be part of a wider Integrity Management Plan and CMS Strategy. For offshore installations the strategy plan should be in line with the verification scheme. For onshore plants, inspection schemes will be part of statutory WSoE for pressure systems.

Tactical plans may jointly cover activities relating to other related corrosion mechanisms, e.g. corrosion under deposit; external atmospheric corrosion.

The plans should be translated into an executable plan and schedule for implementation.

The CMS needs to specify the plan with the activities to be carried out to reduce the identified risk of galvanic corrosion to ALARP. These activities can include:

- current mitigation methods;
- monitoring methods and frequencies;
- definition of KPIs;
- anomaly management, and
- organisational responsibilities for planning, execution, mitigation, monitoring and reporting.

The plan can include:

- competency development plan;
- WSoE at corrosion circuit level, pressure vessels, deadleg register;
- plan instrumentation and data collection;
- Risk Based Inspection (RBI) elements;
- planned maintenance routines, e.g. for inspection;
- inspection work packs in which the responsibilities, coordination, instruction and scope are well defined, and
- attendance of the Corrosion and Chemical Management meetings.

I.7.3 DO

I.7.3.1 Risk profiling

Direct measurement gives the most accurate results. Corrosion modelling and rate predictions can often give variable results; however, this can provide a relative indication on the corrosion rate.

An element of judgement may be required to produce a useful result.

An assessment of corrosion threats or a CRAS should include consideration of galvanic corrosion as a credible corrosion mechanism.

The probability of galvanic corrosion occurring can be predicted with consideration given to following factors:

- dissimilar metals in contact;
- electrochemical potential difference between the two metals (see galvanic series);

- the ratio of area between the two metals (cathode versus anode surface area);
- presence of coating or cladding;
- fluid service (wet or dry), corrosiveness, chemical injection, volatiles (dead crude);
- presence and the conductivity of an electrolyte;
- temperature, and
- inspection observations and NDT data analysis.

I.7.3.2 Organisation

All personnel involved should be made aware of the factors affecting preferential weldment corrosion and be vigilant to recognise the indications of, or changes that are likely to cause, weld corrosion.

Personnel should respond appropriately to any condition recognised as posing a threat and rectify the situation through effective communication with the relevant organisations.

Organisational roles that can be involved include:

- Corrosion and Materials Specialists;
- Production Chemical Specialists and chemical suppliers;
- facilities operations teams;
- Inspection Engineers and NDT contractors, and
- Corrosion and Chemical Management team.

I.7.3.3 Implementing the plan

The strategic plan should be implemented such that the planned activities can be carried out at the specified frequency.

Key requirements for implementing the plan:

- adequate allocation of resources;
- sufficient training of personnel and corrosion awareness, and
- well defined reporting/communication routes, including clear reporting procedures that address and rectify any out of specification incident.

The following production parameters should be monitored:

- pH;
- partial pressure of CO_2;
- temperature;
- water, hydrocarbon and gas flow rates;
- water chemistry for electrolyte conductivity when suspected dissimilar metals are in contact, and
- oxygen concentration, where relevant.

The collected data can be plotted to identify any correlations between process conditions, treatment changes and inspection/corrosion rate trends.

Specialist asset management databases are available to help organise this information. Corrosion damage reports and maintenance reports should also be stored with the data so as to be traceable.

Those data, with the aid of specialist database/tools, should be analysed in order to:

- trend the uniform or localised corrosion rate;
- assess if the mitigation implemented is able to reduce corrosion risk effectively, and
- predict the likely corrosion rate and remaining life of the system or vessel.

I.7.4 CHECK

I.7.4.1 Measuring performance

Performance targets should be set in the strategic plan.

The following can be used as proactive (leading) indicators:

- completion of inspection activities (for known material anomalies) against plan and schedule;
- effectiveness of response/corrective actions taken in the event of out of specification process conditions;
- completion of inspection activities against plan and schedule;
- completion of peer reviews;
- the following can be used as reactive (lagging) indicators;
- frequency of galvanic corrosion related failures, and
- corrosion monitoring results against target corrosion rates based on required life.

The RCA of weld corrosion failures or management system failures will be investigated with the appropriate corrective action(s) recommendation.

I.7.4.2 Investigating accidents/incidents/near misses

Investigate the causes of corrosion and degradation related incidents and accidents in order to reduce the likelihood of reoccurrence.

The investigation will be in accordance with the CM strategic plan which may be part of a wider Integrity Management Plan.

I.7.5 ACT

I.7.5.1 Reviewing performance

The overall performance review should include consideration of a), b) and c) together with verification findings for offshore installations and audit results.

If indicated, the strategic plan may require correction.

The performance review should include the following:

a) Annual (and, if appropriate, quarterly) reviews of weld corrosion mitigation, monitoring and inspection outcomes. Corrective action for these programmes if indicated.

b) Review of performance measures, in particular the assessment of reactive indicators and the overall trends in proactive indicators. Corrective action in strategy, organisation and planning, if indicated.

c) RCA of galvanic corrosion related failures or management system failures with appropriate corrective action recommendations.

I.7.5.2 Learning lessons

Any activity relating to the management of galvanic corrosion should be included in the CMS audits.

I.8 WELDMENT CORROSION

I.8.1 Introduction

One key corrosion mechanism affecting CS weldments is that of preferential weldment corrosion (PWC). The location and morphology of PWC in carbon steel weldments is influenced by a complex interaction of many parameters including: the parent steel composition, the deposited weld composition; the welding procedure; the environment and any CI. Changes in any one of these parameters can cause a significant difference in the weldment corrosion behaviour.

PWC does not affect stainless steels although corrosion is often localised at welds for a variety of reasons including chemical composition, microstructure, surface roughness and heat tint.

Figure I.21: Severe corrosion at the weldment (deep groove along the weld) indicating that weld metal preferentially corrodes in CO_2 environment

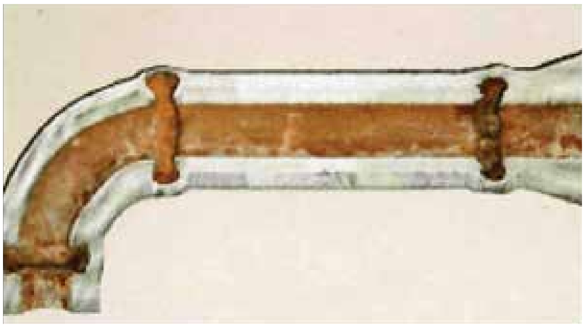


Figure I.22: Severe weldment corrosion in contact with hydrocarbon condensate containing only a small amount of water and saturated with CO_2

I.8.1.1 Weld procedure

Minor changes to the weld metal composition and control of the microstructure are adopted during the weld procedure ensure that mechanical properties of the weld metal are similar to those of the wrought parent pipe.

With manual metal arc (MMA) electrodes, the weld metal is heavily deoxidised resulting in a fine dispersion of small oxides in the molten metal which act as nucleation sites for acicular ferrite, which produces a tough final product. These inclusions, together with possible increases in manganese and silicon, can lead to rapid weld metal corrosion.

With tungsten inert gas (TIG) root runs, the corrosion is often increased due to the deliberate addition of up to 1 % silicon to the welding wire to ensure adequate weld metal fluidity. The silicon forms SiO_2 inclusions in the weld root which may act as sites for corrosion to initiate, perhaps by causing weaknesses in semi-protective corrosion product films.

The effect of microstructure on weldment corrosion is secondary to that of composition. However, with respect to heat-affected zone (HAZ) corrosion, it is generally considered that harder transformed structures (bainite and martensite) will give higher corrosion rates.

I.8.1.2 Differences in weld/parent material composition

It has been thought that PWC may be controlled by making the weld metal cathodic with respect to the adjacent parent pipe and HAZ by making minor additions of more noble elements such as: nickel; chromium; molybdenum; copper; aluminium; vanadium, etc. all of which may assist in the formation of a more protective oxide film. Nevertheless, these additions must be made with caution since over-alloying can result in enhanced HAZ corrosion.

I.8.1.3 1 % Nickel filler weldments

Weld consumables containing nickel are primarily designed to meet strength and toughness criteria. Nickel is an austenite stabiliser, depressing the austenite to ferrite transformation temperature and thereby providing a finer grain size.

An arbitrary 1 % Ni limit was set in accordance with NACE MR01-75 *Materials for Sour Service*. These recommendations have also been applied to sweet systems. 1 % w Ni-containing weld consumables should be used to minimise the risk of PWC. Although satisfactory for the majority of applications, there have been instances where severe PWC has occurred in sweet environments under certain conditions.

Before assessing possible causes of preferential corrosion of Ni-containing weldments, it is worth considering the effect on corrosion of alloy element additions, including Ni, to the parent pipe. For example, it has been reported that CSs with additions of nickel (1,4–3,35 % wt Ni) corrode faster than steels with low Ni and similar Cr contents.

A wide variation in composition is possible within any single pipe specification. The specifications are typically based on mechanical requirements with few compositional restrictions and this must be considered when selecting the consumable for a particular application.

Manufacturers of line pipe, primarily using scrap, produce steels which can have significant levels of residuals, e.g. Ni, Cr, Cu, Mo etc.

These observations are important in interpreting the behaviour of Ni-containing weldments.