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Development
Institute**

Stainless Steel in Waters:
Galvanic Corrosion and its Prevention

A handout prepared for workshops

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SUMMARY

Galvanic corrosion has many facets and the factors that influence it are not always fully understood by those having to cope with the problems: designers, equipment manufacturers and plant engineers in charge of operating facilities.

Stainless steels are widely used in the industries dealing with water such as the production, storage and distribution of drinkable water, the treatment of waste water, the use of seawater for cooling purposes, the production of desalinated water and the use of re-circulated process water.

The stainless steels are very noble alloys and so can be detrimental to less noble metals if the conditions for galvanic corrosion are met.

The aim of this paper is to draw attention to the factors which are involved in galvanic corrosion and, most importantly, provide information on how galvanic corrosion can be avoided or reduced to an acceptable level.

Recommendations are provided about how to benefit from galvanic corrosion by the use of sacrificial anodes for corrosion prevention and the successful application of corrosion resisting metals by observing appropriate rules of design and fabrication.

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1. INTRODUCTION

Stainless steels are important materials in the production and supply of drinking water, and in waste water treatment processes. In some situations it is likely that they will be in contact with more traditional materials as mixed systems where galvanic forces can interfere with the corrosion resistance of the individual metals.

It is the purpose of this paper to provide designers of equipment and operators of plants with a basic understanding of the galvanic behaviour of metals, including stainless steels, and how to recognise and avoid problem areas which may lead to corrosion.

Throughout the paper the generic term "metal" includes "alloys".

2. GALVANIC CORROSION

Although the concept of galvanic (bimetallic) corrosion has been recognised for at least two centuries it continues to be a common cause of failure. It can be visible on automobiles and water taps in households. It is hidden in buried pipelines, in seawater installations and many other industrial installations until failure occurs.

Galvanic corrosion results from one metal being in electrical contact with another where both are in an electrically conducting environment. It is an electro-chemical phenomenon driven by the potential difference between the alloys in that environment. One metal of the couple tends to corrode at a higher rate (the anode) and the other at a lower rate (the cathode) than they may otherwise have done in an uncoupled state in that environment.

The nature of corrosion on the less noble material (the anode) can be uniform or concentrated in small localized areas as pitting or crevice corrosion. The total area affected depends, among other things, on the conductivity of the environment and the relative surface areas of the metals exposed.

Figure 1 provides an impression of the influence of the environment on the corrosion rate of zinc coatings in various locations, either by themselves or in contact with six times the area of stainless steel. In town, on the roof of a steel works and 100 m from the coast, with environments that alternate between dry and wet, the corrosion rates are less if compared with the location where splashing seawater has kept the test pieces wet most of the time. In addition seawater is a more conductive electrolyte than a wet atmosphere in town, at the steel works or some distance away from the coast, leading to relatively higher levels of galvanic corrosion.
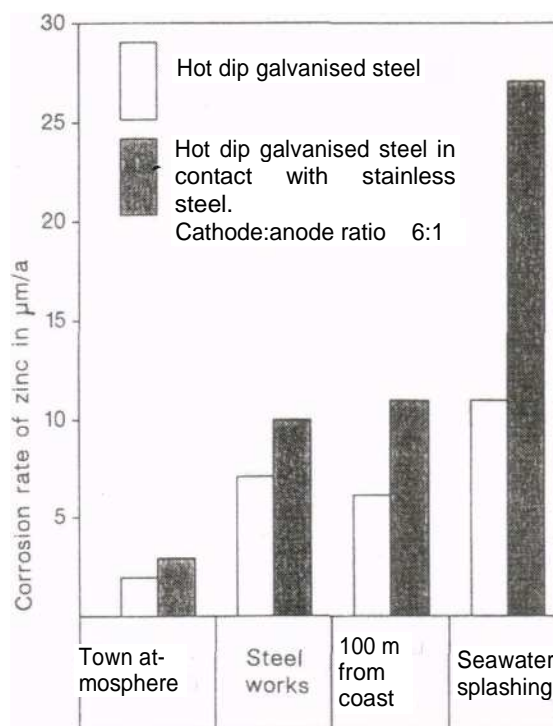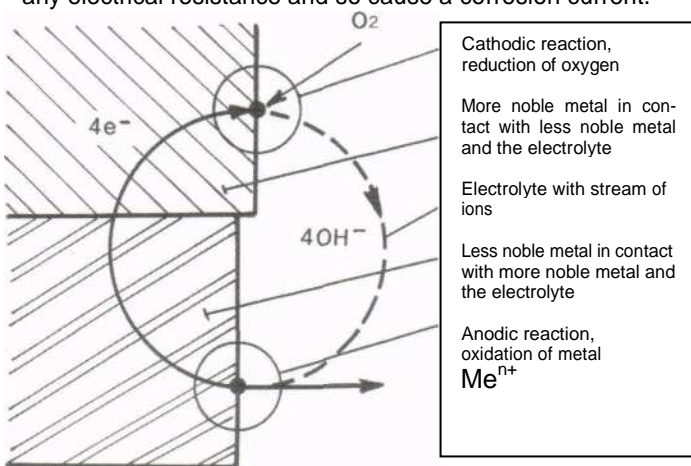

Figure 1

Differences in corrosion rates of hot dip zinc coated steel without and with galvanic coupling to stainless steel in various locations (2)

The stainless steels in their passive state are very noble metals and for this reason can exert considerable influence on galvanic corrosion of less noble metals.

3. CONDITIONS NECESSARY FOR GALVANIC CORROSION TO OCCUR

Galvanic corrosion is an electro-chemical process and in order for galvanic corrosion to occur, the following conditions have to apply:

- Two or more different metals (or a metal and a material which can conduct an electrical current such as carbon) with different free corrosion potentials have to be present.

- An electrical contact between the metals (materials) is necessary.

- All involved metals (materials) have to be in contact with the same electrolyte.

- A sufficient potential difference between the metals must occur in the electrolyte to produce a driving force to overcome any electrical resistance and so cause a corrosion current.

	Cathodic reaction, reduction of oxygen
	More noble metal in contact with less noble metal and the electrolyte
	Electrolyte with stream of ions
	Less noble metal in contact with more noble metal and the electrolyte
	Anodic reaction, oxidation of metal Me^{n+}

At the cathode oxygen dissolved in the electrolyte is reduced and in turn at the anode the less noble metal is oxidized and goes into solution = corrosion

Figure 2: Galvanic Corrosion (1)

If any of these conditions are not met, there will not be any galvanic corrosion. Figure 2 indicates the basic nature of galvanic corrosion.

4. GALVANIC SERIES OF METALS

Since seawater is the most common electrolyte in existence and of much practical importance, most investigations have been on the behaviour of metals and alloys in this medium. A typical seawater galvanic series is shown in Figure 3

which ranks the metals in order of their corrosion potentials, with magnesium being the least noble metal and graphite the most noble material. Also shown are the potentials of the various groups of stainless steel in the passive, corrosion resisting state, and in the actively corroding state when the passivity of the surface is destroyed by the environment (4). The many published galvanic series of metals in seawater differ in detail depending on different conditions of testing. The further apart two metals are in the galvanic series, the more likely galvanic corrosion will occur. In less aggressive waters, the positions of metals in their galvanic series generally remain unchanged but the potentials will be different.

5. GALVANIC CURRENT

The size of the galvanic current, which flows, is a complex value and its corrosive effect, depends on many factors (2)(3):

- The differences in free potential of the metals involved
- The geometric arrangement of the galvanic couple
- The quality of the electrical connection between the metals
- The conductivity of the electrolyte and path length
- The areas of the exposed metal surfaces wetted by the electrolyte
- The availability of oxygen and certain ionic species, particularly chlorides
- The temperature

These factors are discussed in the following sections.

5.1 CORROSION CURRENT AND POTENTIAL

It was assumed for a long time that the amount of corrosion could be predicted from the potential difference of the metals connected with each other. This assumption was wrong. The corrosion current density and with it the corrosion attack, can differ by several orders of magnitude at the same potential difference.

Figure 3: Galvanic series of metals, alloys and graphite in seawater. ▨▨▨ Loss of passivity, active corrosion (4)

The figure shows "Electrode Potential - Relative to the Hydrogen Electrode" with scale: 0.6 0.4 0.2 0 −0.2 −0.4 −0.6 −0.8 −1.0 −1.2 −1.4, with "cathodic" and "anodic" regions, listing:
Magnesium; Zinc; Beryllium; Aluminium alloys; Cadmium; Mild steel, cast iron; Low alloy steel; Austenitic nickel cast iron; Aluminium bronze; Naval brass, yellow brass, red brass; Tin; Copper; 50-50 lead/tin solder; Admiralty brass, aluminium brass; Manganese bronze; Silicon bronze; Stainless steel - types 410, 416; Nickel silver; 90-10 copper nickel; 80-20 copper nickel; Stainless steel - Type 430; Lead; 70-30 copper nickel; Nickel aluminium bronze; Nickel chromium alloy 600; Nickel 200; Silver; Stainless steel - Types 302, 304, 321 and 347; Nickel copper alloys 400, K500; Stainless steel - Types 316, 317; Alloy '20' stainless steels, cast and wrought; Nickel-iron-chromium alloy 825; Titanium; Gold, Platinium; Graphite

It is important whether the anodic or the cathodic part reaction can proceed unhindered or is retarded for example by coatings that are formed on metals such as oxides or deposits. As a result, the predictions based on the galvanic series are not always accurate: corrosion investigations are frequently needed (2) to assess the possible effects of a particular metal combination in a given environment.

5.2 POLARISATION OF METALS

When an electrical current flows between two metals in contact with each other, in the presence of an electrolyte, a shift in the potential of the anodic metal takes place to a more noble value and of the cathodic metal to a less noble value. These changes are called polarisation, the extent of which depends on the metals and the environment involved. In neutral electrolytes the cathode always polarises much more than the anode. Changes in the corrosion potential of individual metals and in the polarity of a couple from published values can result from the presence of complexing ions, from changes in pH, temperature, intense aeration and large differences in the area ratios (5).

The effect of polarisation is a reduction of potential i.e. a reduced driving force for the corrosion current.

5.3 ELECTRICAL CONNECTION

The electrical connection between two or more metals giving rise to galvanic corrosion can be intimate, solid and over a relatively large area resulting in a good electrical connection with low resistance or it can be an unintentional weak point contact. There is no need for the electrical connection to be immersed in the electrolyte. There is also no need for the metals to be in touch with each other. The connection can be some distance away from the electrolyte and be provided by a metallic link such as a wire, a structural member or a common earth grounding (2).

The lower the resistance of the connection, the greater the current, which can flow, and the greater the corrosion will be.

5.4 ELECTROLYTES

Electrolytes can take the form of a bulk liquid, condensation, a hygroscopic or continuously wet deposit, a gasket with capillary properties, a continuously wet crevice, soil or a corrosion product. References (2)(5). A weak electrolyte, such as drinking water, may not be corrosive to metals if the conditions for galvanic corrosion do not apply (5). An increase of the electrical conductivity of the electrolyte causes an increase of the corrosion rate. The presence of

aggressive ions, such as chlorides, increases the conductivity of electrolytes. The values of conductivity can vary widely. Typical values are as follows (5):

	µS/cm
Distilled water	0.5-2
Potable water	150-450
Waste water	1200-2000
Waste water sludge	10 000
Seawater	50 000

Conductivity of some waters

An electrolyte with low electrical conductivity, or when present as a thin film, results in less corrosion generally. However, corrosion can be severe locally where the metals touch each other (5)(8).

5.5 AERATION AND FLOW RATE

The majority of situations in practice involving galvanic corrosion in waters arise under conditions where the cathodic reaction is the reduction of dissolved oxygen and it is controlled by the rate at which oxygen can diffuse to the surface from the bulk of electrolyte. The flow rate of the electrolyte as well has an influence. Stainless steels become more noble with increasing flow rate, their passivity increases and they corrode less.

In neutral electrolytes complete de-aeration can suppress galvanic corrosion but under such anaerobic conditions cathode depolarisation and therefore galvanic corrosion can occur if sulphate-reducing bacteria are present (5).

5.6 SURFACE AREA OF METALS
Under static conditions, galvanic corrosion often depends on the rate of diffusion of dissolved oxygen to the cathode and the weight loss is independent of the size of the anode and proportional to the area of the cathode metal surface. For a constant area of cathodic metal, the weight loss of the anodic metal is constant. If

the area of anodic metal decreases the intensity of corrosion increases as the electric current which flows, concentrates on a smaller area (5).

Under immersed conditions in drinking waters, which have a relatively low electrical conductivity, galvanic corrosion is uncommon if the surfaces of anodic and cathodic metals are of about equal size or if the anodic metal has a much larger surface area (5).

Galvanic corrosion will occur if the anodic metal has a small surface area in relation to the cathode as is the case for screws, bolts, rivets, washers, brazing and welding metals. Therefore fasteners , brazing alloys and weld metals must be cathodic to the parts they join. In seawater, which is a highly conducting electrolyte, the effective surface areas will be greater and the galvanic corrosion will be more severe. Cracks, pinholes or damages in corrosion resisting coatings are almost impossible to prevent and are very vulnerable to accelerated galvanic corrosion (5). The effective ratio of cathodic to anodic surface area is a critical aspect of galvanic corrosion.

Table 1 shows the results of laboratory tests with synthetic seawater with area ratios of 10:1, 1:1 and 1:10. The corrosion rate of a surface area one tenth that of the cathode (stainless steel) is the more severe. An anodic surface area ten times larger than the cathode reduces galvanic corrosion considerably.

Metal	Area ratio St.st./metal	Loss of Metal mm / year
SF-Cu	10:1	1.00
	1:1	0.12
	1:10	0.07
Unalloyed steel	10:1	1.10
	1:1	0.38
	1:10	0.25
Zinc	1:1	0.61
Titanium	1:1	0.01

Table 1. Yearly losses of metals coupled with stainless steel EN 1.4541(X6CrNiTi 18-8) in synthetic sea water
(laboratory tests to DIN 50919) (2)

Table 2 shows the influence on galvanic corrosion of three diffent compositions of stainless steel with a surface ratio of l:l. Since the chromium-nickel alloy is more noble than the ferritic alloys it causes in some cases a slightly increased corrosion rate.

Table 2. Loss of various metals in mm/year coupled with different stainless steels in a 5 mol NaCl-solution at 35 ℃. (2)

Metal	Area ratio	Stainless steel		
		1,4113 X6CrMo1 7-1	1.4512 X2CrTi12	1.4301 X5CrNi18-IO
Unalloyed steel Stee! hot dip galv, ZnAlCu4 AlMg1 SF-CuZn40	1:1	0.62 0.51 0.66 0.15 0.04	0.66 0.51 0.66 0.29 0.04	0.69 0.55 0.69 0.29 0.04

Tables 4 and 5 contain recommendations for the compatibility of metals in two different environments: exposure to the atmosphere and to aerated waste water as for example in aeration basins of waste water treatment plants. The surface areas of the alloys are defined with "large" and with "small". Typically, fasteners (small) are needed in almost every construction (large).

Table 3 shows the results of actual field corrosion tests in seawater with surface areas from 1:1 to 10:1. Again it demonstrates that increasing the cathode surface area causes an increase in the corrosion rate. Stainless steel 1.4439 contains 4.0-5.0% molybdenum and for this reason is a strong cathode.

Stainless steel	Metal	Area ratio Stainless steel / metal	Loss of metal mm / year
1.4439 X3CrNiMoN1 7-13-5	Unalloyed steel	1:1 4:1 10:1	0.31 0.75 2.10
	Al Mg 4.5 Mn	1:1 4:1 10:1	0.17 0.26 0.95
	Cu Ni 10 Fe	4:1	0.07
	Cu Zn 20 Fe	4:1	0.18

Table 3: Loss of various metals coupled with stainless. Field tests in the North Sea (2)

Material with large surface	Material with small surface				
	Unalloyed steel Cast iron	Zinc galv, steel	Al	Cu	Stainless St
Unalloyed steel Cast iron	+ *	-	-	+ *	+ *
Zinc Galv. steel	+ *	+	-	o	+
Al	o / -	o	+	o / -	+
Cu	-	-	-	+	+ / 0
Stainless steel	-	-	0 / -	+	+

+good   o uncertain   -bad   * The galvanic effect of the combination is small **but cannot be recommended because of heavy** self-corrosion of at least one partner.

Table 4: Compatibility of metals in atmospheric exposure (6)

Material with large surface	Material with small surface				
	Unalloyed steel Cast iron	Zinc galv, steel	Al	Cu	Stainless steel
Unalloyed steel Cast iron	+ *	+ *	-	0 / -*	+ *
Zinc Galv, steel	-	+	-	0 *	+ *
A!	-	0 / -	+ *	-	+ *
Cu	-	-	-	+ *	+ *
Stainless steel	-	-	-	o	+
Carbon steel in Concrete	-	-	-	+	+

+ good   o uncertain   - bad

*The galvanic effect of the combination is small but cannot be recommended because of heavy self-corrosion of at least one partner.

Table 5: Compatibility of various metals in aerated waste water (6)

5.7 TIME AND TEMPERATURE EFFECTS

Galvanic corrosion may decrease with time in certain cases but generally will only delay the need for corrective action (5).

An increase in temperature generally increases the rate of corrosion. However, some metals, like zinc and tin, may reverse their polarity at higher temperatures.

5.8 CORROSION PRODUCTS AND HYGROSCOPIC DEPOSITS

Wet corrosion products and hygroscopic deposits tend to accelerate galvanic corrosion.

5.9 GALVANIC CORROSION WITHOUT APPARENT DIRECT PHYSICAL CONTACT

In rare cases copper-dissolving waters deposit the copper on other metals further down stream and can thus produce a galvanic couple and corrosion (5)

6. HOW TO PREVENT GALVANIC CORROSION

Galvanic corrosion can be prevented by the use of electrical insulation between different metals thus stopping formation of the electrical circuit. However, it is important to ensure that the circuit is not accidentally completed by any later plant alterations.

The most effective approach is to design an entire system or installation with the same metal. In most cases stainless steels of different chemical composition can be mixed without detrimental effect but in aggressive electrolytes the steels selected should belong to the same group i.e. chromium-nickel or chromium-nickel-molybdenum groups.

In most mixed metal constructions the stainless steels are strongly cathodic and do not suffer technically relevant galvanic corrosion (2).

It may be possible to increase the life of less noble metals by increasing the surface area exposed to the electrolyte and increasing the cross section thickness. Reference (4).

Where several different metals are installed in a system, those for the most important components (or least accessable components) should be more noble than those chosen for the others. In this way the critical

components will be selectively protected by the less noble metals (4).

Galvanic corrosion can also be prevented by painting or applying another coating to the more noble metal, (such as stainless steel) leaving the less noble metal without protection. A fault in the coating has no effect on the less noble metal. If such a protection is applied to the less noble metal only a fault in the coating will result in rapid local galvanic corrosion (4).

Graphite is the most noble material in the galvanic series of metals and therefore strongly cathodic. Graphite is used in lubricants, as a filler material for plastic materials, rubber and gaskets. Such materials have to be avoided as should gaskets containing embedded wires or metal in other forms.

If valves and pumps made of coated carbon steel, cast iron or nodular iron are combined with a stainless steel pipe system, they should be electrically insulated from the stainless steel by the use of non-conducting bushings, washers and gaskets. Sheet and plate connections can be separated by insulating strip. Figure 4 shows details of an electrically insulated flanged connection.
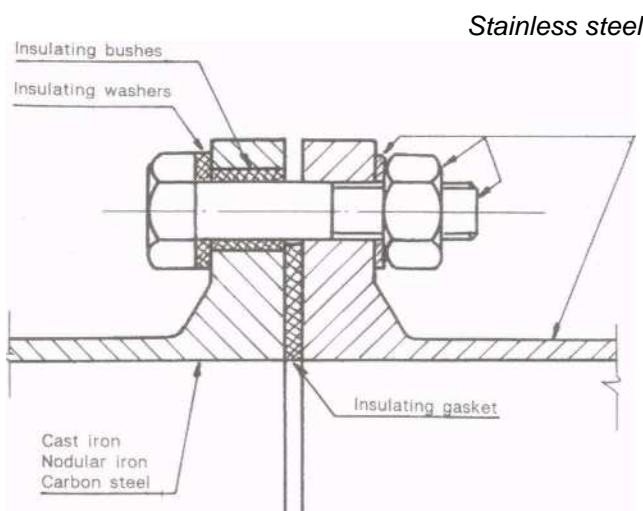
electrode in comparison with the parent metal. Welds have a cast structure and segregations of elements may occur making them less corrosion resistant. The segregation of elements can be reduced by increasing the number of welding passes instead of one heavy pass.

Fasteners have always less surface area than the parts they hold together. Stainless steel fasteners can generally be used on any other metal without fear of galvanic corrosion but occasionally failures are reported where cumulated adverse circumstances resulted in corrosion. Figure 5 shows such a case. The use of fasteners made of carbon steel, galvanized steel, aluminium, brass and bronze should be avoided on stainless steel as they will rapidly corrode.
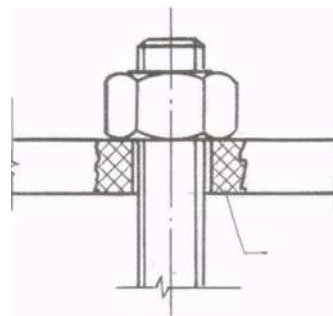

Figure 5: Galvanic corrosion of aluminium plate by stainless steel bolt enlarging hole until connection failed (8)

The ingress of salt water could be reduced by packing the space between bolt and plate with high consistency grease that adheres to metals. Periodic inspection and re-packing is necessary as corrosion is only slowed down but not entirely eliminated.

Low conductivity or a thin film of an electrolyte can result in severe local corrosion where the two metals touch each other.

A better solution is to isolate the stainless steel bolt from the aluminium by using a non-conducting bushing arid washer.

Stainless steel

Figure 4: Electrical insulation of a flanged connection

Welded joints between stainless steel parts that are exposed to highly conducting electrolytes should be more cathodic than the parent metal. This can be achieved by selecting a higher alloyed welding

Special cases where galvanic corrosion can occur in the water industry are reservoirs, wells, filtration plants and other installations for drinking water production and waste water treatment plants. Most of these facilities are older and have been updated at regular intervals. They may contain bare or coated cast iron pipes, coated nodular iron and steel pipes, concrete with carbon steel reinforcing, hot dip galvanised components and, because of continuous danger of corrosion, piping and tubing, pressure doors and frames, ladders, service platforms, handrailing, floor fittings and drain pipes made of stainless steel. In order to control galvanic corrosion in such mixed installations a detailed analysis of the situation will allow the definition of appropriate measures to be taken as discussed in this paper.

7. SACRIFICIAL ANODES PROVIDE PROTECTION AGAINST CORROSION

Galvanic corrosion can be used to advantage in certain cases if an anodic metal is deliberately exposed to corrosion and sacrificed in order to protect part of the structure. Sacrificial anodes tend to reduce the difference of the potentials of the metals involved by polarisation. They can be used to protect stainless steel. Since they corrode, sacrificial anodes need periodic inspection and replacement to maintain the protection.

Figure 6 shows the basic arrangement of cathodic protection with a sacrificial anode. Figure 7 shows a cross section of a tube sheet of a seawater cooled heat exchanger with titanium tubes, carbon steel tube sheet clad with stainless steel and sacrificial carbon steel anodes. They protect the interface between titanium tubes and the stainless steel cladding where crevice corrosion may occur. Figure 8 shows how two sacrificial carbon steel pipe spools protect a valve made of cast iron, ductile iron or cast steel in a stainless steel pipe system.
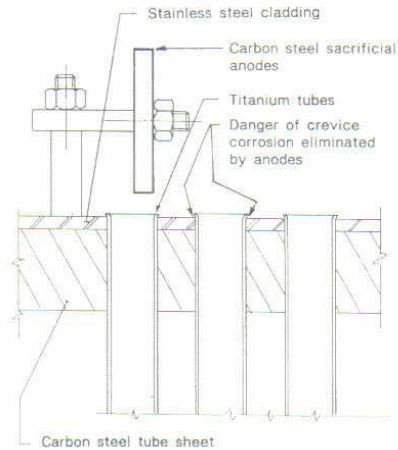

Figure 7: Seawater cooled heat exchanger with titanium tubes, carbon steel tube sheets clad with stainless steel and sacrificial carbon steel anodes. Reference (7)

Sacrificial anodes can take many shapes depending on available space and the surface area to be protected. They can be rectangular pieces cut from plate, short or long bars or, if inserted in pipe systems, flanged pipe spools. In practice magnesium and carbon steel are used for sacrificial anodes. Zinc and aluminium can also be used but their corrosion products are often not acceptable**.**
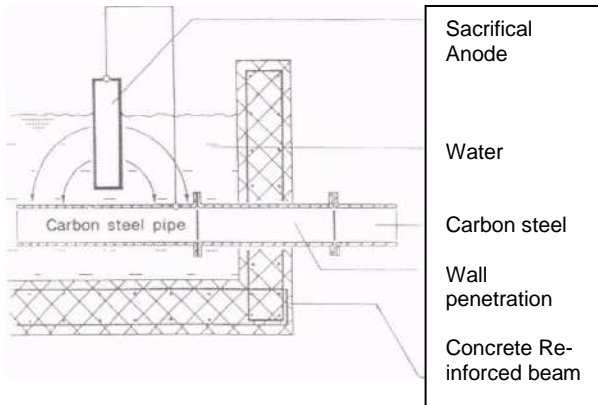

Figure 6: Basic arrangement of cathodic protection with a sacrificial anode (6)

There are limits for the application of this method as it only produces weak protective currents, the process cannot be controlled, the surface area to be protected is limited and the sacrificial anodes suffer rapid corrosion in waste water and seawater which is additional to the corrosion caused by the provision of the protective current (6). Sacrificial anodes need periodic inspection for replacement as the protection against corrosion disappears with a completely dissolved anode. Competent advice should be sought for the design of sacrificial anode systems.

(Wall penetration made of stainless steel {can touch concrete reinforcing with-out danger} with isolated flanges on both sides.)
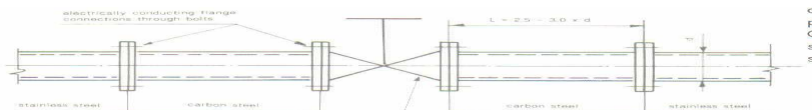

Figure 8: Two sacrificial carbon steel spools protect a valve made of cast iron, ductile iron or cast steel in a stainless steel pipe system (1)

8. SOME EXAMPLES OF GALVANIC CORRO-
SION AND HOW TO PREVENT IT

Liquids in storage tanks are often corrosive at the liquid level and immediately above it due to the exposure to oxygen and condensation. An attempt to protect the tank wall from corrosion can consist of lining it with a stainless steel sheet, with weld overlay or metal spray but as a consequence can result in galvanic corrosion of the carbon steel wall adjacent to the stainless steel lining. Depending on the electrical conductivity of the liquid and anticorrosive measures taken the corrosion can take the form of a groove or of a more shallow but extended removal of carbon steel. In order to control the progress of corrosion inspection at regular intervals is needed. A deep groove can be filled by welding. If a stainless steel filler metal is used the groove forms adjacent to the repair weld. A possible solution to prevent galvanic corrosion would be to coat the entire stainless steel surface. Figure 9 shows such a tank (8).
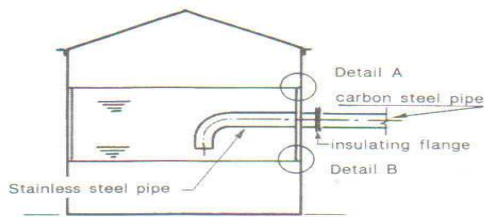
Figure 10 shows a chain that is used in basins of waste water treatment plants. It had carbon steel links and stainless steel pins and bushings (9).The design results in numerous crevices: at the rivet head and where the bushing is pressed into the links. In addition, because the chains work in a highly conductive environment, there was galvanic corrosion between the carbon steel links and the stainless steel parts. The corrosion loosed the pin seats and the pressed in bushings resulting eventually in failure of the links. A better design would have been to construct the entire chain with stainless steel which would have eliminated galvanic corrosion.

Figure 9
General arrangement of a carbon steel storage tank with a stainless steel lining over high and low liquid levels (8)

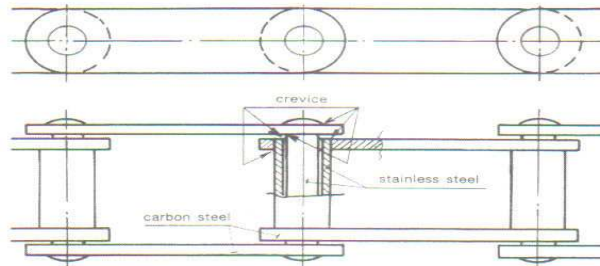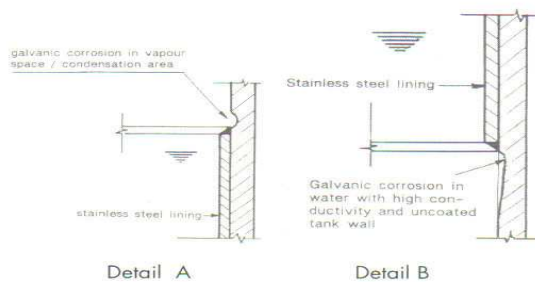**Figure 10**
Chain used in basins of waste water plants made of carbon steel links and stainless steel pins and bushings (9)

Detail A   Detail B

Photograph: Alfred E. Bauer

Corroded aluminium rivets securing a cast yellow brass handle to a nickel stainless steel cooking pan. Brass and stainless steel have a much larger surface than the aluminium rivets and both are more noble (cathodic) resulting in galvanic corrosion. For the rivets either stainless steel or Monel alloy 400 should have been used.

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APPENDIX

10. RECOMMENDATIONS FOR THE SUCCESSFUL DESIGN OF CORROSION RESISTING PLANT

A satisfactory performance against corrosion of a construction can only be achieved if the following recommendations for design and manufacturing are followed (9):

- Selection of the correct alloy(s) considering environment, corrosive medium, operational, shutdown and testing conditions and protective measures.

- Many users of corrosion resisting plant recommend the selection of alloys that have a slightly higher resistance to corrosion than necessary in view of possible process variations and future process modifications.

- A correct design to minimise attack by corrosion.

- Proper manufacture in the shop and erection on the site.

- Final thorough cleaning of the entire construction before putting it into service

- Correct operation and regular planned maintenance

A correct design involves for example:

-Complete and positive drainage from tanks, vessels, apparatus, components, pipes, valves and claddings.

-Access to all surfaces for cleaning purposes

-Avoidance of crevices. They may be caused by:

Gaskets containing voids porosity, fibres, metallic

reinforcements and chlorides-dirt and deposits-coatings-

welds with incomplete penetration,craters and overlaps-bolt

heads,nuts and washers-spot welds

-Use of rounded corners

-Avoid welds in corners

-Avoid narrow spaces where deposits can accumulate

-Provide sufficient high flow velocity to prevent deposits

- Select the most advantageous surface finish

- Avoid mixture of different metals. Use preferentially metals of the same group such as:

  - Mild steel, low alloy steel, cast iron, cast steel
  - Bronzes, brasses, tin, copper (except nickel-aluminium bronze)
  - Copper-nickel alloys, lead
  - Nickel-aluminium bronze, nickel-chromium alloy 600, nickel 200
  - Austenitic chromium-nickel stainless steels
  - Austenitic chromium-nickel-molybdenum stainless steels, alloy 20, nickel-iron-chromium alloy 825