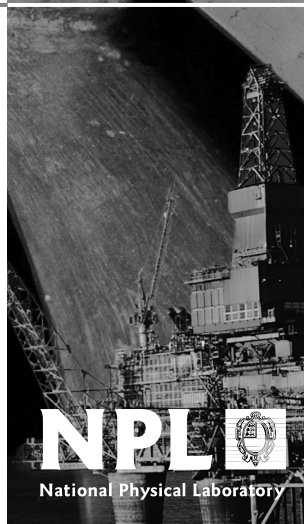


# Corrosion control checklist

**CORROSION**

STOP IT NOW!



**NPL**  
National Physical Laboratory

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## Corrosion control begins during design

**The cost** Failure to control corrosion can lead to:

- increased costs
- reduced safety
- negative environmental impact

Corrosion costs the United Kingdom a significant percentage of its GNP. Engineering employs similar materials world-wide, therefore comparable proportions of corrosion costs are found in other industrialised countries. It has been estimated that **a quarter of all corrosion problems could be prevented easily by using well established techniques.** The economic, social or ecological consequences of major corrosion failures can be ruinous. Corrosion increases running costs and reduces plant efficiency, availability and product quality.

**The cause** Corrosion results from the chemical interaction of a metal with its environment and may be uniform in nature or localised. Physical and chemical conditions of the environment influence both the rate and type of attack, the nature of corrosion products, the way in which metallic properties themselves are affected, and the corrosion control measures needed.

**Advances in materials technology** The continued development of material technology and monitoring and control methods mean the potential for saving corrosion costs is higher today, and that for favourable applications very much greater savings are now achievable. In some types of project, uncontrolled corrosion could amount to 30% of the total commitment of capital expenditure.

**Design awareness and the life-cycle** Good control of corrosion requires the awareness and co-operation of the entire design team, including engineers and designers not only in each specialised discipline but in project management and cost control. Adequate means for collecting, reporting and recording corrosion information from operational situations must also be planned.

**Multi disciplinary activity** The design of most functional components and systems is a multi-disciplinary activity. Large engineering design contractors integrate the materials, welding, painting and corrosion control functions into the design team on a project basis. This allows decisions on materials and corrosion control to be implemented from the earliest stages of design and construction, and ensures all materials and corrosion control requirements are adequately documented. In smaller organisations this is commonly achieved through independent materials and corrosion consultancy.

**Control** Throughout the life-cycle of a metallic fabrication. Due attention to design, choice of materials and manufacturing processes, transportation, storage, start-up, operation, inspection, maintenance and shut-down, will reduce the cost of corrosion and risk of failure. Effective and timely consideration of design, corrosion monitoring, corrosion control and the consequences of corrosion failure not only reduce the extent and cost of corrosion but enhance the safety, functionality, useful lifetime and appearance of the fabrication.

**This checklist** is not for dealing with corrosion after it has happened, but for preventing corrosion at the design stage.

## Design considerations

Factors that can influence corrosion:

### Environment

Chemical  
Natural  
Storage, transit

### Stress

Residual stress from fabrication  
Static, variable and alternating operating stresses

### Shape

Joints and flanges  
Crevices and deposits  
Trapped and contained liquid

### Compatibility

Metals with metals  
Metals with other materials  
Quality control of materials

### Movement

Flowing fluids  
Parts moving in fluids  
Two- and three-phase flow  
Entrained solids  
Vibration and pulsing

### Temperature

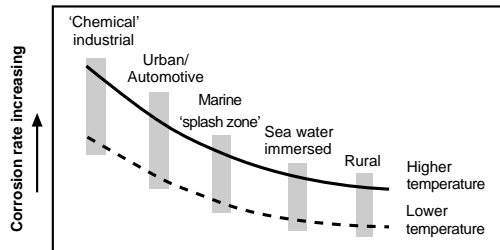
Oxidation, scales and tarnishes  
Heat-transfer effects  
Molten deposits  
Condensation and dewpoints

### Control

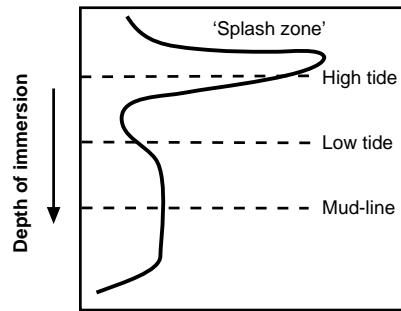
Surface cleaning and preparation  
Coatings  
Cathodic protection  
Inhibitors  
Data logging  
Inspection  
Planned maintenance

Metal	Industrial Air (microns/year)	Marine Air (microns/year)	Rural Air microns/year
Aluminium	0.81	0.71	0.025
Copper	1.19	1.32	0.58
Lead	0.43	1.41	0.48
Zinc	5.13	1.60	0.86
Mild steel	13.72	6.35	5.08
Weathering steel	2.54	3.81	1.27

How different types of atmosphere affect corrosion rates with two years exposure  
 (Note: 10 microns = 0.01 mm)



Corrosion rates and influence of aggressive environments



Corrosion rates at different positions for steel partly immersed in sea water

**Rule of thumb**

For many aqueous corrosion reactions a 30 °C temperature change could result in a 10-fold change in corrosion rate, while a 20 °C temperature change will approximately double the corrosion rate.

## Environment

The type of environment to which a material is exposed is a major factor in determining the type and severity of corrosion undergone. Minor constituents of the surroundings can be critical, aggravating or suppressing corrosive attack. Geographical location is also important, as is the influence of weather and season at the time of construction, repair, etc.

### Natural environments

#### **Air**

Rural (farming, fertilisers, ammonia)  
Coastal, marine (chloride)  
Industrial, urban (sulphur dioxide, soot and acid rain)

#### **Waters**

Rivers, lakes, wells, water pipelines, dams; sea water (tidal, "splash zone"), estuaries, harbours (in most of these, chlorides are significant contaminants, as well as a variety of corrosive biological agents).

#### **Soils**

Clays, chalk, loam; drainage; acidity; access of air; bacterial action (sulphate reducing bacteria).

### Chemical environments

Urban and industrial atmospheres  
Environmental pollutants creating aggressive mists  
Interior of reaction and storage vessels in chemical plant.

### Other environments

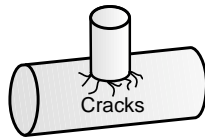
Embedded metals may react with non-metallic materials such as wood, plastics, and concrete. The porosity of some of these media allow contact with stagnant water.

### Temperature

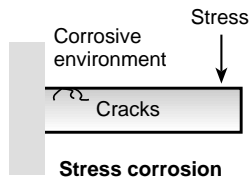
Increasing temperature usually causes increased rates of corrosion. A notable exception is when temperature increase reduces relative humidity or dries out the environment completely.

### Incident radiation

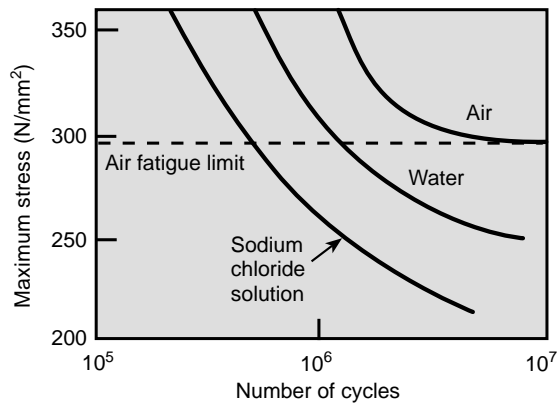
Sunlight, ultraviolet light and thermal radiation, can activate short-lived reactive chemical species from contaminants in the environment, aggravating corrosion.



**Cracks from residual stresses in poor fabrication (weld).**



**Common locations for stress corrosion cracking**



**Effect of environment on fatigue behaviour of mild steel**

## Stress

General or uniform corrosion causes progressive loss of cross-section and increased stress levels, while uneven and localised corrosion causes high stress concentrations. Design should control extremes of stress and environment arising at any time in the life-cycle of the structure.

*Think about the following ...*

- Residual and thermal stresses arising from fabrication
- Transportation shocks and vibration
- Installation
- Performance and pressure testing, leading to over-stressing, test fluids corrosion
- Operating and fault conditions
- Maintenance, including effects of modifications and repairs

### Static stresses

The environment both inside and outside a structure can affect the strengths of the materials specified. For each alloy, *Stress Corrosion Cracking (SCC)* requires specific environmental corrosive conditions, with the alloy subjected to a critical tensile stress (residual or applied). SCC is very dangerous because of the progressive nature of the cracking, with ever rising risks of rupture, leakage, or loss of function.

### Fluctuating stresses and corrosion fatigue

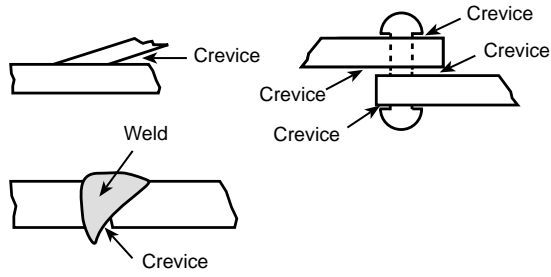
In a corrosive environment the stress level at which it could be assumed a material has infinite life is lowered or removed completely. Corrosion fatigue and fretting are both in this class. Much lower failure stresses and much shorter failure times can occur in a corrosive environment compared to a situation where the alternating stress is in a non-corrosive environment.

### Hydrogen effects and stress

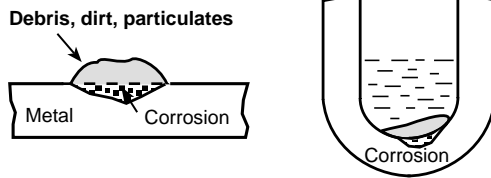
Atomic hydrogen released by cathodic reactions during corrosion can enter metals, causing several significant types of damage. Hydrogen has a strong tendency to travel along stress gradients and accumulate where there are high tensional stresses. By several mechanisms, this can cause cracking in steels. Hydrogen may also be introduced during welding or due to cathodic protection.



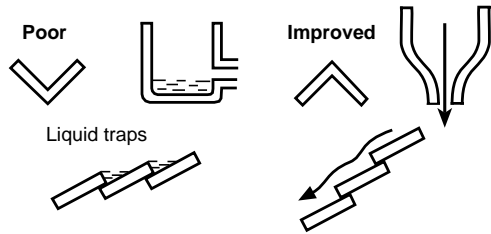
### Crevices



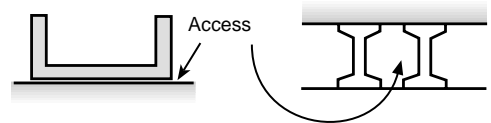
### Deposits



### Drainage



### Accessibility



### Design tips

*Good inspection will often minimise premature corrosion damage.  
Avoid traps and provide access for cleaning.*

## Shape

"Trap" geometry is poor geometry. Corrosion may be fostered by retention of liquids or contact of the metal surface with a local environment differing from that expected by the designer. Features shown opposite encourage poor drainage, possibilities for solution concentration, differential aeration and poor access for inspection, repairs or maintenance.

*Think about the effect of the following ...*

### Access

Inspection and maintenance requires adequate access to all parts of a structure. Design must allow for easy replacement of material where the risk of corrosion and the consequences of failure are significant.

### Joints, flanges

Crevices let stagnant liquid accumulate, causing locally accelerated corrosion from differential aeration. There can also be contact between dissimilar metals. Slower drying at joints can increase concentration of aggressive salts. Consider the use of appropriate and safe solvents.

### Welds

Poor weld profile, lack of fusion and stitch welding can all lead to crevices and stress raisers.

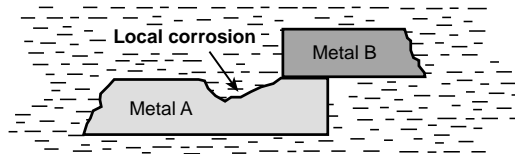
### Deposits

Debris on horizontal surfaces can give shielding corrosion (differential aeration corrosion). Corrosion products and water forming scales can affect heat transfer and cause temperature differentials that can lead to corrosion.

### Liquid traps

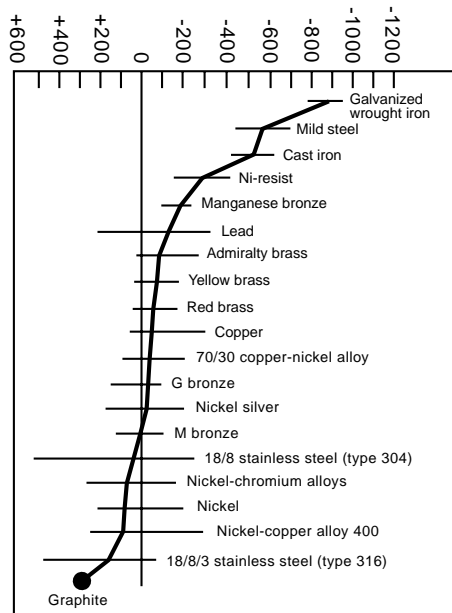
Poorly draining areas can result in increased corrosion generally. Increased corrosion may also occur at the water line zone.

**Dissimilar metal contact**



**Dissimilar metal contact**

Potential relative to saturated calomel half-cell (mV)



**Galvanic series of metals in aerated sea water (courtesy of International Nickel)**

**Rule of thumb**

*For most steels a 1 amp current will corrode about 1 g/h of metal, for aluminium this is about 1/2 g/h.*

## Compatibility of materials

From the point of view of corrosion, metals may be incompatible with each other or with other materials they contact. The relative areas of two different metals in electrical contact can affect their corrosion rates. This is particularly damaging if the more "active" (anodic) metal has a smaller area.

*Think about the following sources of incompatibility ...*

### Within the metal

Fabrication may create differences in metallurgical structure or alloy composition, allowing local attack, such as:

- End-grain attack on exposed cross-sections of susceptible wrought metals
- Weld decay
- Knife-line attack (intergranular corrosion) near welds, especially in some stainless steels
- Selective corrosion (or dealloying) of some materials. Dezincification is loss of zinc from brass.

### Within the environment

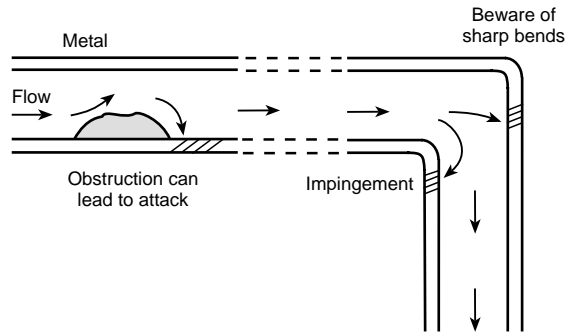
A fluid may contain active metallic species that can lead to local corrosion. For instance, dissolved copper in contact with metallic aluminium can cause pitting.

### Contact with other materials

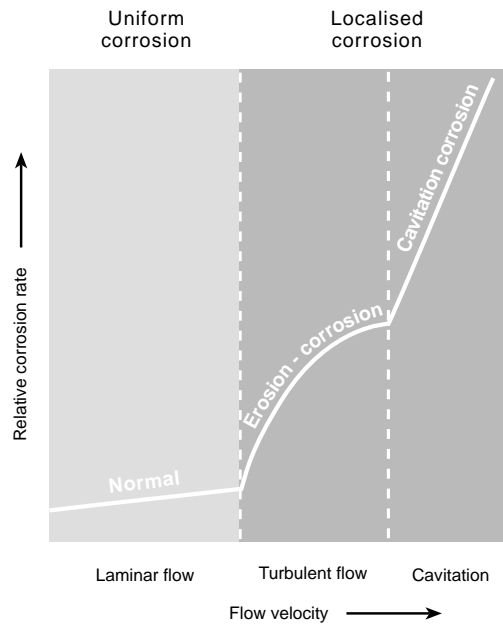
Care may be necessary when a metal is in contact with non-metallics, such as plastics, wood, concrete and some electrically conductive mineral species, such as magnetite (magnetic iron oxide) and iron sulphide.

### Welds

Changes in weld metal and base metal composition and structure result in galvanic corrosion or intergranular effects, such as weld decay in unstabilised stainless steel.



Effect of flow geometry on corrosion rate



Effect of flow rate of fluid on relative corrosion rate

**Design tip**

*Prevent localised corrosion by reducing the flow rate and avoiding turbulence*

## Movement

Movement of the corrosive environmental agent and the movement of parts can seriously affect the corrosion rates and mechanisms.

*Think about the following ...*

### Flowing fluids

The flow of fluids relative to a metal can increase the corrosion rate. Erosion corrosion may become significant at high rates of flow when the flow changes from laminar to turbulent.

**Impingement** Caused when liquids impact on a metal surface. Damage can arise due to:

- free-falling droplets
- mist droplet impingement in pipe vapour flow at changes of flow direction or internal irregularities
- jetting of droplet-laden vapours
- dripping of liquids onto surfaces
- agitation
- damage due to impingement of solids (erosion).

**Cavitation** Damage can occur in regions associated with steep liquid velocity gradients, where vapour-filled voids may form and collapse supersonically, causing shock waves that damage the metal surface by severe localised attack through massive momentum transfer to the metal. Areas subject to local boiling, and dead-end-locations can be prone to similar damage.

### Parts moving in the fluid

Care is needed when considering metals for moving components such as pump impellers or stirrers, which are susceptible to erosion, impingement and cavitation.

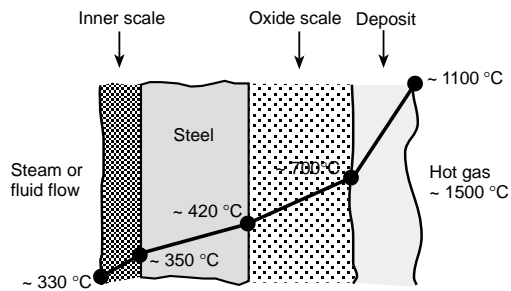
### Two-phase and multi-phase fluids

Bubbles, particles and immiscible liquids (e.g. oil and water) in moving fluids can increase the corrosion rate. Differentially wettable solids tend to partition into the most highly wetting liquid phase, increasing its apparent density and tendency to sink.

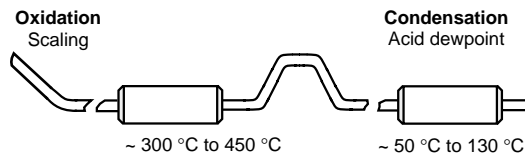
**Material oxidation limits - guide only**

Alloy	Generic composition	Scaling temperature in air (°C)*
Mild steel	Fe 0.25C	480
Alloy steel	Fe 1Cr 0.5Mo 0.5C	565
Alloy steel	Fe 12Cr 1Mo	650
Grade 316 stainless steel	Fe 18Cr 13Ni 2.5Mo 0.08C	900
Grade 310 stainless steel	Fe 25Cr 20Ni 0.25C	1150
Nickel-base superalloys	e.g. Ni-Cr-Fe or Ni-Mo alloys	~1100
Cobalt-base superalloys	e.g. Co-Ni-Cr-W alloys	over ~1150

\* This refers to temperatures below which oxidation rates are negligible, but does not account for creep property limitations or polluted atmospheres, which can reduce these temperatures.



Temperature gradients and heat transfer across steel tubes carrying steam



Influx gas oxidation and dew-point corrosion

**Rule of thumb**

For many oxidation reactions a 20 °C temperature change will result in a 10 times change in the oxidation rate.

Note: compare this with the rule of thumb on page 4.

## Temperature

Higher temperatures generally increase corrosion rates. However, corrosion needs a liquid phase and, if drying occurs, higher temperatures may be beneficial. If operating temperatures are too high a material will oxidise, forming scale. Thick scales and metal loss result in overheating, from loss of water cooling or absence of insulation. Heat transfer will be progressively impeded as scales or deposits thicken.

*Think about the following ...*

### Environmental factors

Polluted gases can accelerate attack and are often accompanied by heat. Examples are, sulphurous flue gases such as sulphur dioxide and sulphur trioxide, halogens such as chlorine compounds, nitrogen oxides, carbon particles such as soot and hydrolysable organic compounds.

### Source of heat

Heat sources include:

- electrical heating elements
- steam heating
- heat from ongoing process chemistry
- fuel combustion – flue gases and deposits
- flame impingement
- molten metals
- friction and wear
- solar radiation and radiation from gas flares
- processes such as drying
- engines and motors

Remember, some sources of heat can be very localised such as electrical contacts or heaters of any type. In many cases thermal cycling occurs, this can accelerate the corrosion rate and introduce combined effects. Small temperature changes can produce marked changes in corrosion resistance.

### Condensation – dewpoint effects

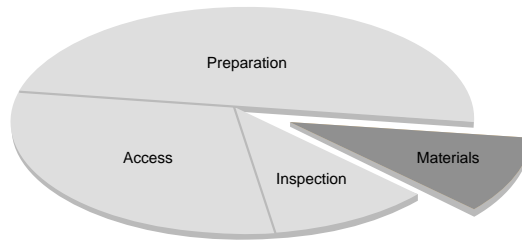
When hot combustion gases cool, condensation may give rise to acid dewpoint conditions. This can occur with chimneys, vehicle exhausts, power and process plant and certain horticultural environments.



### Coating types and their lives

Protection duration needed	Requirement for coating type
Short term 1-5 years	Single pack materials such as alkyds, emulsions and acrylics are usually in this category
Medium term 5-10 years	Two-component materials such as zinc-rich primers, epoxies, polyurethanes, usually at lower thicknesses
Long term/high performance 10+ years	Two-component materials such as metal spray, epoxies, polyurethanes, glass flake and FRP

Chart depicting materials costs as a small proportion of overall costs



**General rule of thumb**

*There is no simple rule of thumb for selecting the most suitable coating system. The advice of an independent expert .*

## Use of paints and coatings

Painting or coating is the mainstay of corrosion prevention for materials not inherently corrosion resistant. This is a matter of economics. Paints and coatings are generally applied at low additional cost to the least expensive structural materials. Minimising the additional cost is an integral part of ensuring the economic viability of painting and coating as a corrosion control solution. Therefore paints and coatings generally do not last as long as the operating lifetime of the material to be protected, the ability to maintain the coating systems is vital.

### Factors in selection of paint or coating systems

When choosing a system, several alternatives may appear to be technically acceptable, and it is necessary to identify relevant factors affecting corrosion control and cost.

The most important of these are:

- high project cost, prestige or failure consequences may warrant choice of high performance materials
- type of substrate to be coated
- track record of the selected system for the environmental and operating conditions expected
- life expectancy of coating to first maintenance
- ease of access to substrate work surface
- quality of applicator and contractor
- compliance with legislative and environmental requirements
- delivery logistics
- maintenance conditions, and compatibility with existing materials

**Costing of a single system** The costing of a single system must be a compromise between various individual cost factors, typically including:

- Materials
- Labour
- Transport

**Example calculation of paint costs**

Noting that, by definition,  $100 \times \text{DFT}/\text{WFT} = \text{VS}\%$   
 And, consequently, that  $\text{WFT} = \text{DFT} \times 100/\text{VS}\%$ , then for:

Solventless paint 1: VS% = 97.5% at £4.80 per litre  
 Solvent-free paint 2: VS% = 100.0% at £4.90 per litre  
 Solvent-bound paint 3: VS% = 50.0% at £2.70 per litre

Paint 1 WFT =  $250 \times 100/97.5 = 256.41$  micron  
 Paint 2 WFT =  $250 \times 100/100 = 250$  micron  
 Paint 3 WFT =  $250 \times 100/50 = 500$  micron

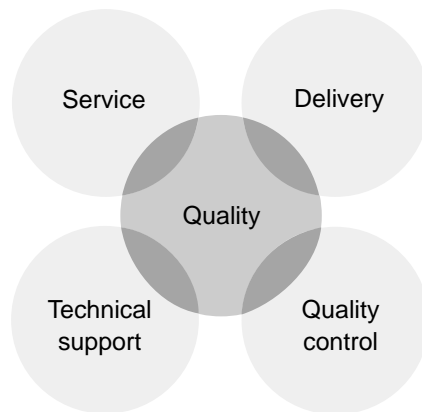
Accordingly, the paint volumes to cover 1 square metre are (litres):

Paint 1 =  $256.41 \times 100 \times 100/10,000 \text{ ml} = 0.256$  litres  
 Paint 2 =  $250 \times 100 \times 100/10,000 \text{ ml} = 0.250$  litres  
 Paint 3 =  $500 \times 100 \times 100/10,000 \text{ ml} = 0.500$  litres

And the costs are:

Cost/m<sup>2</sup> for paint 1 =  $£4.80 \times 0.256 = £1.23$   
 Cost/m<sup>2</sup> for paint 2 =  $£4.90 \times 0.250 = £1.22$   
 Cost/m<sup>2</sup> for paint 3 =  $£2.70 \times 0.500 = £1.35$

Note: DFT equals dry film thickness, WFT equals wet film thickness



**Peripheral factors affecting the choice of supplier**

**Rule of thumb**

*For paints and coatings there is no rule of thumb, always consult an expert.*

### ***Cost comparisons of different coating systems***

These are more complex, and such aspects as painting conditions, substrate preparations, humidity, temperature and time available must all be considered.

### ***Estimation of painting costs***

Painting costs are estimated either as total cost or cost per square metre. Several objective and subjective factors are important for estimating valid painting costs.

### ***Overspray of Fabrication***

Even on uncomplicated substrates this can amount to 5% despite efficient airless spraying.

### ***Wind Loss***

Paint application in the open in high wind can cause losses of 20% to 50%.

### ***General Losses***

Factors such as exceeding pot life, pilferage and spillage need consideration in estimating paint consumption.

### ***Absorbent Surfaces***

A factor of 2% to 5% should be considered for inadequately sealed wood surfaces, as they tend to absorb paint into the substrate.

### ***General***

Even with well trained operatives, 'on the job' inspection and good QA/QC procedures, the paint estimator should add a baseline factor of 25% to the paint consumption calculation. All other listed factors will then need to be considered.

### ***Coverage rates and paint types***

Solventless and solvent-free coatings are invariably much more expensive than normal solvent-bound types but, for a given DFT, they yield a much higher coverage rate than solvent-bound types. The example opposite illustrates this for the three coating types at a coverage of 200 micron DFT. In this case, the use of solvent-free materials (paint 2), though more expensive in cost per litre, actually works out cheaper.

## Control

Various corrosion control measures are available, one or more of which might be appropriate. The full life-cycle must be considered as corrosion may occur at any stage. Materials selection, fabrication, shape and cost are all significant. Corrosion control measures must be able to reduce risk to a quantifiable and appropriate low level where the consequences of failure are serious.

*Think about the following as approaches to achieving the desired design life ...*

### **Corrosion allowance**

Metal added to the design thickness against general corrosion loss is generally 0.5 mm to 6.0 mm for many engineering purposes. Where the progress of depleting the corrosion allowance must be recorded, "day one" corrosion thicknesses should be measured at appropriate locations as a measurement base-line. Mill tolerances of plate, pipe and other shapes are not precise enough as a basis for loss-of-thickness estimation.

### **Effect of Surface condition**

Corrosion rate is aggravated by surface contaminants such as millscale, surface rust, dust, oil, grease and by defects, such as scratches, machine marks, pits, dents, ridges from local stresses, porosity and casting defects.

### **Effect of Surface cleaning**

Different surface preparations and cleaning procedures are required for different operating conditions and for different types of coating. The range of cleaning procedures includes mechanical, chemical, steam and flame methods.

### **Coatings**

The choice of coating is related to its intended function. This can include coating for visual decorative appearance, temporary coating for transport or storage, using wax, grease or other water repellent, and long-term corrosion protection, using organic, inorganic or metallic coating systems.

Access for inspection and maintenance is always essential because of the risk of gaps ("holidays") in

the original coating, and because the lifetime of coatings is usually shorter than the plant or equipment design lifetime.

### **Cathodic and anodic protection**

This is the control of metal potentials to reduce the corrosion rate. It is suitable for immersed and underground conditions for plant, recirculatory systems and natural environments. This can be done by either using sacrificial electrodes or using an impressed current.

### **Inhibitors**

These are substances added in small concentrations to reduce the corrosion rate. Liquid-phase or vapour-phase varieties are used in closed systems such as central heating, power boilers, sealed packaging. In chemical process systems having a throughput of process fluids, batch or continuous inhibitor addition is practised.

### **Maintenance**

Planned maintenance is desirable. Records of installation, maintenance and repair dates are needed. Corrosion inspection and testing can be useful.

### **Corrosion control and system history**

Repairs or local changes in a system may alter the requirements for corrosion inhibitors or chemicals required for process control. Time-related corrosion changes in a system must also be accounted for; the internal surface of a pipe increases as it is roughened by corrosion. This can increase the amount of surface active inhibitive chemicals needed to control corrosion.

### **Quality control**

- Confusion of materials must be avoided, especially if repairs are to be carried out in a planned maintenance programme.
- Materials for some specially corrosive applications require full traceability from manufacture through to installation.
- Where resistance to corrosion depends on correctly applied welding technology, it should be carried out to appropriately designed and qualified welding procedures.

### **Do's**

- ✓ minimise stress raisers, sharp profiles, threaded screw roots and other stress concentration effects
- ✓ protect materials in environments conducive to stress corrosion cracking
- ✓ prevent local concentration of contaminants such as in crevices, absorbent thermal insulation, hollows or droplet evaporation points
- ✓ always consult relevant codes of practice
- ✓ select a resistant material
- ✓ consider the use of inhibitors
- ✓ if necessary use a protective coating
- ✓ protect materials in transit
- ✓ design for streamline flow
- ✓ increase thickness of material where necessary
- ✓ minimise stress levels and design to even out variations
- ✓ filter out abrasives and contaminants
- ✓ consider the effect of combined action such as stress regime, flow, thermal variations
- ✓ avoid galvanic couples
- ✓ contact experts for specific advice
- ✓ remember, corrosion is a surface phenomenon and consider the performance of the specified surface in service not just the bulk material properties
- ✓ remember, it is not always possible to prevent corrosion occurring but it is always possible to take measures to control it sufficiently
- ✓ a well designed system should incorporate features that facilitate maintenance and inspection.
- ✓ the control of corrosion is a team activity. Consult manufacturers, users and other service providers to ensure that the control measures can be carried out as expected.

### ***Dont's***

- X** substitute a material with a proven track record on the basis of cost saving, without considering possible loss of corrosion control
- X** use data without checking that the environment and conditions in use relate to those under which the data was collected
- X** ignore good practice guidelines
- X** ignore the possibility that small changes in the environment or operating conditions could have a dramatic affect on corrosion control
- X** forget to allow for excursions outside of the bounds of normal operating conditions
- X** assume maintenance procedures that seem easy to carry out on paper can be carried out as easily in practice
- X** leave corrosion control until the last step in the design process and rely on remedial control measures
- X** ignore the environmental impact associated with control measures, coatings or maintenance procedures
- X** extend the times for cleaning processes or surface treatments beyond manufacturers recommendations as this can create problems
- X** ignore the possibility that combined action such as stress and corrosion could significantly reduce life-times
- X** use rate data for uniform corrosion to estimate life-times for localised corrosion
- X** use calculation of corrosion rates as a basis for design, when a better design could eliminate the corrosion problem.



## Glossary

**Anion** A negatively charged ion.

**Anode** The electrode of a cell where reacting elements lose electrons (become oxidised).

**Bimetallic corrosion (galvanic corrosion)** Corrosion of two different electrically contacting metals immersed in the same electrolyte.

**Biocide** A chemical additive that kills life forms.

**Calcareous scale** (chalky scale) A scale precipitated from salts dissolved in hard waters.

**Corrosion allowance** Sufficient additional metal thickness above that required for design code load requirements, to compensate for loss of metal thickness.

**Cathode** The electrode where the reacting cations gain electrons.

**Cathodic protection (CP)** Deliberate decrease of the corrosion rate by making the potential of a metal structure immersed in an electrolyte more negative (more cathodic).

**Cation** A positively charged ion.

**Cavitation** See page 13.

**Corrosion current** The electric current flowing in the metal between the electrodes of a corrosion cell due to the corrosion reaction.

**Corrosion-erosion (erosion-corrosion)** Combined action of corrosion and erosion that removes any inherent or applied protective film, causing localised material loss.

**Corrosion fatigue** Localised corrosion cracking from fluctuating stresses where the corrosive environment eliminates the classical fatigue endurance limit.

**Corrosion monitoring** Any method used to observe or measure the progress of corrosion.

**Corrosion potential** The overall potential of a metal due to a corrosion reaction.

**Crevice corrosion** Localised corrosion at, and resulting from, corrosive conditions within a fine crevice formed between two opposing surfaces, of which at least one is a metal. See pages 8-9.

**De-aeration (de-oxygenation)** The removal of oxygen either from gases or aqueous liquids.

**Deposit attack** A form of crevice corrosion due to solids deposited on a surface.

**De-alloying (selective dissolution)** Preferential corrosive removal of an alloy component, creating mechanically weak areas.

**Differential aeration** The variation in dissolved oxygen concentration in the solution contacting the metal surface enhancing corrosion.

**Electrode** In an electrochemical cell, the location at which electric charge enters or leaves a metallic surface (see also anode and cathode).

**Electrode potential** The difference in electrical potential between an electrode and the electrolyte it is contacting.

**Electron** The electrically charged particle liberated from neutral atoms that carries electric current through the metallic path in an electrochemical cell.

**Electrolyte (electrically conductive solution)** A solution in which the passage of electrical charge occurs.

**EMF (electromotive force) series of metals** The tabulation of standardised metallic electrode potentials

**Filiform corrosion** Corrosion with the appearance of filaments that progress across a metal surface leaving a meandering track.

**Fretting corrosion** Deterioration by corrosion or oxidation at the contact area between metals subjected to small repeated displacements under load. See pages 6-7.

**Galvanic series** A listing of metals and alloys showing the order of corrosion potential in a specific environment, commonly sea water.

**Galvanising** The coating of iron and steels with a layer of zinc and iron-zinc compounds, by immersion in a bath of molten zinc.

**Graphitic corrosion** A form of de-alloying corrosion of grey cast iron in which the strong metallic constituents are removed leaving a mechanically weak residue of corrosion inducing graphite.

**Half-cell (electrode)** One of the electrodes, and its immediate environment, in an electrochemical cell.

**Hydrogen electrode (standard hydrogen electrode)** An electrode at which the equilibrium  $H^+ + e^- \rightleftharpoons \frac{1}{2}H_2$  is established on a platinum surface. At specified standard conditions this electrode is assigned an arbitrary reference potential of 0.00 volts, against which to make all other potential

measurements, including the calibration of more practical secondary reference electrodes.

**Hydrogen embrittlement** Embrittlement caused by the entry of atomic hydrogen into a metal.

**Impingement attack** A form of localised corrosion-erosion caused by impinging flow. See pages 12-13.

**Intergranular attack** Preferential corrosion at grain boundaries.

**Inhibitor** A substance added to an environment in small concentrations to reduce the corrosion rate to an economic or safe level.

**Knife-line attack** Severe highly localised attack, resembling a sharp cut into the metal, close to the fusion line of a weld in a stabilised austenitic stainless steel.

**Millscale** Thick oxide layer produced on metals during hot rolling. The term is usually applied to scale on steels.

**Passivity** Decrease in the corrosion rate of a metal in solution resulting from the formation of a thin and generally non-visible protective film of metal corrosion products.

**pH value** A number that indicates the acidity or alkalinity of a solution. A pH of 7 is neutral, a pH greater than 7 is alkaline and a pH less than 7 is acidic.

**Pitting (pitting corrosion)** Highly localised corrosion in which penetration into the metal occurs, with consequent danger of perforation.

**Potential (electrode potential)** Potential difference at an electrode-solution interface defined with reference to another specified electrode. See **reference electrode**.

**Reference electrode (standard electrode)** A half-cell of reproducible and known potential by means of which an unknown electrode potential may be determined.

**Scale** Thick visible oxide film formed during the high-temperature oxidation of a metal.

**Sensitisation** Increased susceptibility to attack, in a corrosive environment resulting from heating, such as from welding usually in stainless steels.

**Stress-corrosion cracking** Cracking due to the combined action of corrosion and an essentially static internal or applied tensile stress. See also **corrosion fatigue** and pages 6-7.

**Tarnish (patina)** Dulling, staining or discoloration due to formation of thin films of corrosion or oxidation.

## Additional information

There are many sources of corrosion information, ranging from brief data-sheets, wall-charts and pamphlets to fully detailed and specific technical papers, textbooks, standards and specifications. Obviously care is needed when extracting information. The general sources detailed below have been selected because they can provide a useful starting point for further study. Expert advice can supplement available information.

### General reading and quick reference

#### **NACE Corrosion Engineer's Reference Book**

2nd edition, edited by R S Treseder, R Baboian and C G Munger (Ed.)  
NACE 1991 ISBN 0 915567 82 2

#### **Corrosion**

3rd revised edition, edited by L L Schreir, revised by R A Jarman and G T Burstein  
2 vols Butterworth-Heinemann 1994 ISBN 0 7506 1077 8

#### **ASM Handbook Volume 13 Corrosion**

10th edition, ASM 1987 ISBN 0 87170 0190

#### **Corrosion Engineering**

M G Fontana and N D Greene 3rd revised edition  
McGraw-Hill 1985  
ISBN 007 021463 8

#### **Corrosion Engineering Handbook**

P A Schweitzer  
Dekker 1996 ISBN 0 8247 9709 4

#### **Life Prediction of Corrodible Structures**

R N Parkin  
NACE 1994 ISBN 1 877914 60 6

#### **Materials Optimizer**

Fulmer Research Institute, Slough 1974

#### **Smithells Metals Reference Book**

7th Edition, edited by E A Brandes and G B Brook  
Butterworth-Heinemann, 1997  
ISBN 0 7506 36246

### Useful contacts

National Corrosion Service,  
National Physical Laboratory, Teddington, TW11 0LW  
Tel: 020 8943 6142 E-mail: ncs@npl.co.uk

Institute of Corrosion,  
4 Leck House, Lake Street,  
Leighton Buzzard, Beds, LU7 8TQ  
Tel: 01525 851771

National Association of Corrosion Engineers  
Website: [www.nace.org/nacehome.html](http://www.nace.org/nacehome.html)

Institute of Materials  
1 Carlton House Terrace, London SW1Y 5DB  
Tel: 020 7451 7300

## CHECKLIST ON CORROSION CONTROL

The first edition of this checklist was compiled for the Department of Industry on the advice of the Corrosion Education and Training Working Party. The guide was written as an aid for designers, engineers and others, to help encourage greater attention to corrosion factors in design detail.

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This second edition has been revised for the Department of Trade and Industry by Mr J W S Newman of Lithgow Associates and edited by Mr Bill Nimmo of NPL.