

THE PREVENTION OF CORROSION

R. M. E. DIAMANT, MSc, DipChemE, AMInstF
Lecturer in Chemistry and Applied Chemistry
University of Salford

Applied Chemistry Series

Number 2

General Editor

Professor G. R. Ramage, University of Salford

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Preface

Corrosion is responsible for annual losses amounting to millions of pounds.

The reason for this is certainly not a lack of fundamental research in the field. Ulick R. Evans, FRS, one of the world's foremost authorities on corrosion, lists in his filing system over 9,000 research publications dealing with corrosion.

Despite the amount of scientific research carried out in the field of corrosion over the years, the average engineer seems to know little about the subject. Numerous really serious design errors from the corrosion aspect are constantly being committed, even by the largest industrial undertakings. For example, in the motor industry quite elementary design blunders have been made, causing heavy and often dangerous corrosion to take place in vehicles.

The fault must lie in bad communication. In the science of corrosion prevention, as in other fields, there is a huge chasm between the scientist in his laboratory and the practical designer in his drawing office.

This book is intended to bridge the gap. Its aim is the same as its title: 'The prevention of corrosion'. It is meant as a textbook for engineering and metallurgy students, and as a concise practical guide for engineers in industry. Basic theoretical treatment is confined to the first chapter, the rest being mainly devoted to practical aspects of corrosion and its prevention.

At the end of each chapter there is a bibliography to enable readers to study the subject further. It must be appreciated that this fairly short book cannot hope to do more than to serve as an introduction to this huge subject, but I am convinced that this is precisely what is needed. No attempt is made to provide a comprehensive work and those requiring to know more about the subject are referred to the treatises published by U. R. Evans and L. L. Schreir

EVANS, U. R., *The corrosion and oxidation of metals*, Arnold, London (1960)

—, *The corrosion and oxidation of metals*, First supplementary volume, Arnold, London (1968)

SCHREIR, L. L., *Corrosion*, 2 volumes, Newnes, London (1963)

I would like to express my thanks to Professor G. R. Ramage, Chairman of the Department of Chemistry and Applied Chemistry at the University of Salford, for the help he has given me in the preparation of this book.

R. M. E. DIAMANT
University of Salford

SI Conversion Factors

| | |
|--------------------|--|
| Length | 1 yard = 0.914 4 metre 1 foot = 0.304 8 metre 1 inch = 25.4 millimetre |
| Area | 1 yard ² = 0.836 127 metre ² 1 foot ² = 0.092 903 metre ² 1 inch ² = 645.16 millimetre ² |
| Volume | 1 yard ³ = 0.764 555 metre ³ 1 foot ³ = 28.316 8 decimetre ³ (litre) 1 inch ³ = 16.387 1 centimetre ³ |
| Capacity | 1 UK gallon = 4.546 09 decimetre ³ (litre) 1 US gallon = 3.785 41 decimetre ³ (litre) |
| Mass | 1 UK ton = 1,016.05 kilogramme 1 US ton = 907.184 4 kilogramme 1 hundredweight (UK) = 50.802 3 kilogramme 1 pound = 0.453 592 37 kilogramme 1 ounce = 28.349 5 gramme 1 grain = 0.064 798 9 gramme |
| Temperature | $^{\circ}\text{F} = 9/5^{\circ}\text{C} + 32$ $\text{K} = ^{\circ}\text{C} + 273.15$ $^{\circ}\text{R} = 1.8 \text{ K}$ |
| Heat | 1 British thermal unit = 1.055 06 kilojoule 1 centigrade heat unit = 1.899 108 kilojoule 1 kilocalorie = 4.186 8 kilojoule |
| Power | 1 horsepower = 0.745 7 kilowatt 1 horsepower (metric) = 0.735 499 kilowatt |
| Pressure | 1 atmosphere = 101.325 kilonewton/metre ² 1 inch of mercury = 3.386 389 kilonewton/metre ² 1 centimetre of mercury = 1.333 22 kilonewton/metre ² 1 bar = 10 ⁵ newton/metre ² 1 inch water gauge = 249.082 newton/metre ² 1 centimetre water gauge = 98.063 8 newton/metre ² 1 pound (f)/foot ² = 1.488 164 newton/metre ² 1 pound (f)/inch ² = 6.894 76 kilonewton/metre ² 1 ton (f) (UK)/foot ² = 107.252 kilonewton/metre ² |

xvi SI CONVERSION FACTORS

$$1 \text{ ton (f) (UK)/inch}^2 = 15\cdot444 \text{ 3 meganewton/metre}^2 = 15\cdot444 \text{ 3 newton/millimetre}^2$$

Density

$$1 \text{ ton (UK)/yard}^3 = 1\cdot328 \text{ 94 tonne/metre}^3$$

$$1 \text{ pound/foot}^3 = 16\cdot018 \text{ 5 kilogramme/metre}^3$$

$$1 \text{ pound/inch}^3 = 27\cdot679 \text{ 9 kilogramme/decimetre}^3$$

Concentration

$$1 \text{ grain/100 foot}^3 = 0\cdot022 \text{ 883 5 gramme/metre}^3$$

$$1 \text{ ounce/gallon (UK)} = 6\cdot236 \text{ gramme/decimetre}^3$$

$$1 \text{ grain/gallon (UK)} = 14\cdot254 \text{ gramme/metre}^3$$

Thermal conductivity

$$1 \text{ Btu/foot hour degF} = 1\cdot730 \text{ 73 watt/metre degC}$$

$$1 \text{ Btu inch/foot}^2 \text{ hour degF} = 0\cdot144 \text{ 228 watt/metre degC}$$

$$1 \text{ kilocalorie/metre hour degC} = 1\cdot163 \text{ watt/metre degC}$$

Thermal conductance

$$1 \text{ Btu/foot}^2 \text{ hour degF} = 5\cdot678 \text{ 26 watt/metre}^2 \text{ degC}$$

$$1 \text{ kilocalorie/metre}^2 \text{ hour degC} = 1\cdot163 \text{ watt/metre}^2 \text{ degC}$$

Moisture and air diffusivity

$$1 \text{ grain inch/foot}^2 \text{ inch mercury hour} = 1\cdot453 \frac{\text{milligramme metre}}{\text{meganewton second}}$$

$$= 5\cdot231 \frac{\text{gramme metre}}{\text{meganewton hour}}$$

Note: Thermal conductivities can be expressed as either watt/metre degC or watt/metre kelvin

BASIC SI UNITS

| Physical quantity | Name of unit | Symbol for unit |
|---------------------------|--------------|-----------------|
| Length | metre | m |
| Mass | kilogramme | kg |
| Time | second | s |
| Electric current | ampere | A |
| Thermodynamic temperature | kelvin | K |
| Luminous intensity | candela | cd |

Symbols for units do not take a plural form.

SUPPLEMENTARY UNITS

| Physical quantity | Name of unit | Symbol for unit | Definition of unit |
|---------------------------------|----------------|-----------------|---|
| Plane angle | radian | rad | } Dimensionless |
| Solid angle | steradian | sr | |
| Energy | joule | J | $\text{kg m}^2 \text{s}^{-2}$ |
| Force | newton | N | $\text{kg m s}^{-2} = \text{J m}^{-1}$ |
| Power | watt | W | $\text{kg m}^2 \text{s}^{-3} = \text{J s}^{-1}$ |
| Electric charge | coulomb | C | A s |
| Electric potential difference | volt | V | $\text{kg m}^2 \text{s}^{-3} \text{A}^{-1} = \text{J A}^{-1} \text{s}^{-1}$ |
| Electric resistance | ohm | Ω | $\text{kg m}^2 \text{s}^{-3} \text{A}^{-2} = \text{V A}^{-1}$ |
| Electric capacitance | farad | F | $\text{A}^2 \text{s}^4 \text{kg}^{-1} \text{m}^{-2} = \text{A s V}^{-1}$ |
| Magnetic flux | weber | Wb | $\text{kg m}^2 \text{s}^{-2} \text{A}^{-1} = \text{V s}$ |
| Inductance | henry | H | $\text{kg m}^2 \text{s}^{-2} \text{A}^{-2} = \text{V s A}^{-1}$ |
| Magnetic flux density | tesla | T | $\text{kg s}^{-2} \text{A}^{-1} = \text{V s m}^{-2}$ |
| Luminous flux | lumen | lm | cd sr |
| Illumination | lux | lx | cd sr m ⁻² |
| Frequency | hertz | Hz | cycle per second |
| Customary temperature, <i>t</i> | degree Celsius | °C | $^{\circ}\text{C} = \text{K} - 273.15$ |

FRACTIONS AND MULTIPLES

| Fraction | Prefix | Symbol | Multiple | Prefix | Symbol |
|------------|--------|--------|-----------|--------|--------|
| 10^{-1} | deci | d | 10 | deka | da |
| 10^{-2} | centi | c | 10^2 | hecto | h |
| 10^{-3} | milli | m | 10^3 | kilo | k |
| 10^{-6} | micro | μ | 10^6 | mega | M |
| 10^{-9} | nano | n | 10^9 | giga | G |
| 10^{-12} | pico | p | 10^{12} | tera | T |
| 10^{-15} | femto | f | | | |
| 10^{-18} | atto | a | | | |

Conversion Factors for Determining Corrosion Penetration

A penetration rate of 1 g/m².day equals:

| <i>• Metal</i> | <i>Density</i> | <i>mil/year</i> <i>(0.001 in/year)</i> <i>1.44/density</i> | <i>μm/year</i> <i>368/density</i> |
|----------------|----------------|--|--------------------------------------|
| Aluminium | 2.72 | 5.3 | 133 |
| Beryllium | 1.85 | 7.9 | 200 |
| Brass | 8.48 | 1.7 | 43 |
| Cadmium | 8.70 | 1.6 | 40 |
| Cobalt | 8.90 | 1.6 | 40 |
| Copper | 8.92 | 1.6 | 40 |
| Germanium | 5.35 | 2.7 | 68 |
| Gold | 19.3 | 0.74 | 19 |
| Iron or steel | 7.86 | 1.8 | 46 |
| Lead | 11.35 | 1.25 | 31 |
| Magnesium | 1.75 | 8.25 | 210 |
| Molybdenum | 10.2 | 1.41 | 36 |
| Nickel | 8.90 | 1.6 | 40 |
| Niobium | 8.55 | 1.68 | 43 |
| Osmium | 22.5 | 0.64 | 16 |
| Palladium | 11.4 | 1.25 | 32 |
| Platinum | 21.45 | 0.67 | 17 |
| Silver | 10.5 | 1.37 | 35 |
| Tantalum | 16.6 | 0.87 | 22 |
| Tin | 7.30 | 2.00 | 51 |
| Titanium | 4.55 | 3.2 | 81 |
| Tungsten | 19.3 | 0.74 | 19 |
| Uranium | 18.7 | 0.78 | 20 |
| Zinc | 7.15 | 2.00 | 51 |
| Zirconium | 6.45 | 2.25 | 57 |

Table of Metals Not Recommended for Contact With Various Chemicals

The metals considered are the following :

| | | |
|---------------------|-----------------------|---------------|
| Aluminium: Al | Aluminium bronze: | Tin: Sn |
| Brass: Cu/Zn | Al/Cu | Copper: Cu |
| Mild Steel: m.s. | Bronze: Cu/Sn | Cast iron: Fe |
| Cupro-nickel: Cu/Ni | Duriron: Fe/Si | Nickel: Ni |
| Silver: Ag | Stainless steel: s.s. | Platinum: Pt |
| Zirconium: Zr | Tantalum: Ta | Titanium: Ti |

Inclusion in brackets means that the metal in question is satisfactory at room temperature but not at elevated temperatures. Metals omitted are normally stable up to 100°C.

Acetic acid (dil.): (Al), Cu/Zn, Fe, Pb, m.s., Sn
 Acetic acid (conc.): Cu/Zn, Fe, Pb, m.s., (s.s.), Sn
 Acetic anhydride: Cu/Zn, (Cu/Sn), m.s. (s.s.), Sn
 Acetone: (Pb), (m.s.)
 Acetylene: Al/Cu, Cu, Cu/Sn, (Pb), Cu/Ni, (Sn)
 Alkyl chlorides: Al, Cu/Zn, (Pb), (m.s.), (Sn)
 Aluminium chloride: Cu/Zn, Fe, (Fe/Si), m.s., Ni, (Cu/Ni), (s.s.), (Sn)
 Aluminium sulphate: Cu/Zn, Fe, m.s., (Ni), (Cu/Ni), (s.s.), (Sn)
 Ammonia: Cu/Al, Cu/Zn, (Fe), Cu, Cu/Sn, (Pb), Ni, Cu/Ni, (Sn)
 Ammonium chloride: Cu/Al, Cu/Zn, (Fe), Cu, Cu/Sn, (Pb), m.s., (Cu/Ni), (s.s.), (Sn)
 Aniline: Cu/Al, Cu/Zn, Cu, Cu/Sn, (Pb), (Cu/Ni), (Sn)
 Aqua regia: all with the exception of Ag and Ta; (Ti)
 Benzene: (Pb), (m.s.)
 Benzoic acid: Fe, Pb, m.s., (Sn)
 Boric acid: (Al), Fe, m.s., (Cu/Ni),
 Bromine: Cu/Al, Cu/Zn, Fe, Cu, Cu/Sn, (Fe/Si), (Pb), m.s., Ni, s.s., Sn, Ti
 Calcium chloride: Cu/Zn, (Fe), (Pb), m.s., s.s., (Sn)
 Carbon disulphide: m.s., (Ni), (Cu/Ni), (Sn)
 Carbonic acid: Cu/Al, Cu/Zn, Fe, Cu/Sn, Pb, m.s., (Ni)
 Carbon tetrachloride: Al, (Pb), (m.s.)
 Chlorine (dry): Fe, Sn, Ti, (Zr)
 Chlorine (wet): Al, Cu/Al, Cu/Zn, Fe, Cu, Cu/Sn, (Pb), m.s., Ni, (Cu/Ni), s.s., Sn, Zr
 Chloroform: Al, (Fe), (Pb), (m.s.)
 Chromic acid: Al, Cu/Al, Cu/Zn, Fe, Cu, Cu/Sn, (Fe/Si), m.s., Ni, Cu/Ni, Ag, s.s.
 Citric acid: Cu/Zn, Fe, m.s., (Cu/Ni),
 Copper chloride: Al, Cu/Zn, Fe, Cu, Cu/Sn, (Pb), m.s., Ni, Cu/Ni, Sn, Zr

xx TABLES OF METALS

Copper sulphate: Al, Cu/Zn, Fe, Cu, Cu/Sn, (Pb), m.s., (Ni), (Cu/Ni), Sn, Zr
 Ethanol: (Pb)
 Ethyl acetate: (Pb), m.s. (Sn)
 Fatty acids (higher): Cu/Zn, Fe, m.s., (Sn)
 Ferric chloride: All except Ta, Ti; (Fe/Si), (Pt)
 Ferrous sulphate: Al, Cu/Al, Cu/Zn, Fe, Cu, Cu/Sn, (Pb), m.s., Ni, (Cu/Ni), Ag, Sn
 Fluorine gas (dry): Cu/Zn, Fe, (Pb), Fe/Si, Ta, Sn, Ti, Zr
 Fluorine gas (wet): Al, Cu/Al, Cu/Zn, Fe, Pb, Fe/Si, m.s., s.s., Ta, Sn, Ti, Zr
 Fluosilicic acid: all except Ni, Cu/Ni, Pt, Ag
 Formalin solution (50%): (Al), (Cu/Zn), (Fe), (Pb), (m.s.), (Sn)
 Formic acid: (Al), Fe, m.s., (Cu/Ni), (s.s.), Sn
 Glycerol: (Pb), (m.s.)
 Hexamine: Al, Cu/Al, Cu/Zn, Fe, Cu, Cu/Sn, (Pb), m.s. (Cu/Ni) (Sn)
 Hydrobromic acid (conc.): all except Pt, Ta, Ti, Zr
 Hydrobromic acid (dil.): ditto plus (Ni), (Cu/Ni), (Fe/Si)
 Hydrochloric acid (conc.): all except Pt, Ta, Ti, Zr, (Cu/Al)
 Hydrochloric acid (dil.): ditto plus Ag, (Fe/Si), (Ni), (Cu/Ni).
 Hydrocyanic acid (conc.): Cu/Al, Cu/Zn, Cu, Cu/Sn, (Pb), (M.s.), (Cu/Ni), (s.s.), (Sn)
 Hydrofluoric acid (60%): all except Cu/Ni, Pt, Ag; (Ni)
 Hydrogen peroxide (conc.): Cu/Al, Cu/Zn, Fe, Cu, Cu/Sn, Fe/Si, Pb, m.s., Ni, Cu/Ni, Ag, (Sn), Ti
 Hydrogen sulphide (wet): (Fe), (Pb), (Cu/Ni), Ag.
 Lead acetate: Cu/Al, Cu/Zn, Fe, Cu, Cu/Sn, Fe/Si, Pb, m.s., (Cu/Ni), (Sn)
 Mercuric chloride: all except Pt, Ta, Ag, Ti, Zr
 Mercury metal: Al, Cu/Al, Cu/Zn, Cu, Cu/Sn, Pb, (Cu/Ni)
 Naphthalene: (Pb), (m.s.)
 Nickel chloride, nitrate and sulphate: Al, Cu/Al, Cu/Zn, Fe, Cu, (Pb), m.s., Sn
 Nitric acid (dil.): all except Pt, s.s., Ta, Ti, Zr; (Fe/Si)
 Nitric acid (conc.): all except Fe/Si, Pt, Ta, Ti, Zr; (s.s.)
 Nitric acid (fuming): all except Fe/Si; (Al), (m.s.), (s.s.), (Ta), (Zr)
 Oils (all kinds): (Pb), (m.s.)
 Oxalic acid: (Al), (Cu/Zn), Fe, Pb, m.s., Ni, (Cu/Ni), (s.s.), (Ti)
 Perchloric acid: all except Fe/Si, Pt, Ag, Ta, Ti, Zr
 Phenol: (Cu/Ni), (Sn)
 Phosphoric acid (conc.): Al, Cu/Al, Cu/Zn, Fe, Cu, Cu/Sn, (Pb), m.s., Ni, (Cu/Ni), (s.s.) Sn, (Ti), (Zr)
 Phosphoric acid (dil.): (Al), (Cu/Al), Cu/Zn, Fe, Cu, Cu/Sn, m.s., Ni, (Cu/Ni), Sn
 Phosphorus trichloride and pentachloride: Al, Cu/Al, Cu/Zn, (Fe), Cu, Cu/Sn, (Cu/Ni), s.s., Sn, (Zr)
 Pyridine: Cu/Al, Cu/Zn, Cu, Cu/Sn, (Pb), (Cu/Ni).

Quicklime (CaO): (Al), (Pb), (Sn)
 Sea-water: (Fe), (Pb), m.s., (Ni), (s.s.),
 Silver nitrate: Al, Cu/Al, Cu/Zn, Fe, Cu, Cu/Sn, Pb, m.s., Ni, Cu/Ni, Sn
 Sodium carbonate: (Al), (Pb), (Sn)
 Sodium (and potassium) hydroxide: Al, Cu/Al, (Fe), (Fe/Si), Pb, (m.s.),
 Sn
 Sodium chlorate: Cu/Zn, Fe, Pb, m.s., (Cu/Ni), (Sn)
 Sodium chloride: Cu/Zn, m.s., (s.s.)
 Sodium hypochlorite: all except Fe/Si, (Pb), Pt, (Ag), Ta, Ti, Zr
 Sodium peroxide: Al, Cu/Al, Cu/Zn, Cu, Cu/Sn, Pb, m.s., (Cu/Ni), (s.s.),
 Sn
 Sodium sulphate: (Pb), m.s.
 Sodium sulphide: Al, Cu/Al, Cu/Zn, Cu, Cu/Sn, (Fe/Si), m.s., Ag, (s.s.),
 Sn, (Ti)
 Sulphur: Cu/Al, Cu/Zn, (Fe), Cu, Cu/Sn, Pb, Ag, (Sn)
 Sulphur dioxide (dry): (Fe), (Cu/Ni)
 Sulphur dioxide (wet): Cu/Zn, Fe, Cu, Fe/Si, Cu/Sn, Pb, m.s. Ni, Cu/Ni,
 (s.s.), Sn
 Sulphur trioxide: Al, Fe, Cu/Ni, s.s., Sn, Ti, Zr
 Sulphuric acid (dil.): Al, Cu/Zn, Fe, Cu/Sn, m.s., Ni, (Cu/Ni), s.s., Sn
 Sulphuric acid (conc.): Al, Cu/Al, Cu/Zn, (Fe), Cu, Cu/Sn, (Pb), (m.s.),
 Ni, Ag, (s.s.), Sn, Ti, Zr
 Sulphuric acid (fuming): (Al), Cu/Al, Cu/Zn, Cu, Cu/Sn, Pb, (m.s.), Ni,
 Cu/Ni, Ag (s.s.), Sn, Ti, Zr
 Sulphur chlorides: all except Pt, Ta, (Fe), (Pb), (Cu/Ni)
 Tannic acid: Fe, Pb, m.s., (Sn)
 Tartaric acid: Fe, m.s.,
 Tin salts: all except Pt, Ta, Ti, Zr (Fe/Si), (Ag)
 Trichloroethylene: (Fe), (Pb), (m.s.)
 Zinc salts: Al, Cu/Al, Cu/Zn, Fe, Cu, Cu/Sn, (Fe/Si), (Pb), m.s., s.s., Sn

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