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

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

BUSINESS BOOKS LIMITED
London

First published 1971

ISBN 0 220 66889 2

This book has been set 10 on 11 pt Times Roman and printed in England by Clarke, Doble & Brendon Ltd. for the publishers, Business Books Limited (Registered office: 180 Fleet Street, London EC4); Publishing offices: Mercury House, Waterloo Road, London SE1

MADE AND PRINTED IN GREAT BRITAIN

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	°F = 9/5°C + 32
	K = °C + 273·15
	°R = 1·8 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

1 ton (f) (UK)/inch^2 = 15·444 3 meganewton/metre^2 = 15·444 3 newton/millimetre^2

Density

1 ton (UK)/yard^3 = 1·328 94 tonne/metre^3
1 pound/foot^3 = 16·018 5 kilogramme/metre^3
1 pound/inch^3 = 27·679 9 kilogramme/decimetre^3

Concentration

1 grain/100 foot^3 = 0·022 883 5 gramme/metre^3
1 ounce/gallon (UK) = 6·236 gramme/decimetre^3
1 grain/gallon (UK) = 14·254 gramme/metre^3

Thermal conductivity

1 Btu/foot hour degF = 1·730 73 watt/metre degC
1 Btu inch/foot^2 hour degF = 0·144 228 watt/metre degC
1 1 kilocalorie/metre hour degC = 1·163 watt/metre degC

Thermal conductance

1 Btu/foot^2 hour degF = 5·678 26 watt/metre^2 degC
1 kilocalorie/metre^2 hour degC = 1·163 watt/metre^2 degC

Moisture and air diffusivity

$$1 \text{ grain inch/foot}^2 \text{ inch mercury hour} = 1{\cdot}453 \frac{\text{milligramme metre}}{\text{meganewton second}}$$

$$= 5{\cdot}231\,6 \frac{\text{gramme metre}}{\text{meganewton hour}}$$

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	$kg\ m^2\ s^{-2}$
Force	newton	N	$kg\ m\ s^{-2} = J\ m^{-1}$
Power	watt	W	$kg\ m^2\ s^{-3} = J\ s^{-1}$
Electric charge	coulomb	C	A s
Electric potential difference	volt	V	$kg\ m^2\ s^{-3}\ A^{-1} = J\ A^{-1}\ s^{-1}$
Electric resistance	ohm	Ω	$kg\ m^2\ s^{-3}\ A^{-2} = V\ A^{-1}$
Electric capacitance	farad	F	$A^2\ s^4\ kg^{-1}\ m^{-2} = A\ s\ V^{-1}$
Magnetic flux	weber	Wb	$kg\ m^2\ s^{-2}\ A^{-1} = V\ s$
Inductance	henry	H	$kg\ m^2\ s^{-2}\ A^{-2} = V\ s\ A^{-1}$
Magnetic flux density	tesla	T	$kg\ s^{-2}\ A^{-1} = V\ s\ m^{-2}$
Luminous flux	lumen	lm	cd sr
Illumination	lux	lx	$cd\ sr\ m^{-2}$
Frequency	hertz	Hz	cycle per second
Customary temperature, t	degree Celsius	°C	$°C = K - 273{\cdot}15$

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:

Metal	*Density*	*mil/year (0·001 in/year) 1·44/density*	*μm/year 368/density*
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: Al/Cu	Tin: Sn
Brass: Cu/Zn	Bronze: Cu/Sn	Copper: Cu
Mild Steel: m.s.	Duriron: Fe/Si	Cast iron: Fe
Cupro-nickel: Cu/Ni	Stainless steel: s.s.	Nickel: Ni
Silver: Ag	Tantalum: Ta	Platinum: Pt
Zirconium: Zr		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

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

Contents

List of Figures