



Granta Design - CES Durability e-book reference

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Science note

Electrochemical corrosion

Corrosion is the degradation of a metal by an electro-chemical reaction with its environment (see also [Durability: acids and alkalis](#)). Figure 1 illustrates the idea of an electro-chemical reaction. If a metal is placed in a conducting solution like salt water, it dissociates into ions, releasing electrons, as the iron is shown doing in the figure, via the *ionization reaction*

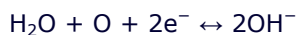


The electrons accumulate on the iron giving it a negative charge that grows until the electrostatic attraction starts to pull the Fe^{++} ions back onto the metal surface, stifling further dissociation. At this point the iron has a potential (relative to a standard, the *hydrogen standard*) of -0.44 volts. Each metal has its own characteristic corrosion potential (called the *standard reduction potential*), as plotted in Figure 2.

If two metals are connected together in a cell, like the iron and copper samples in Figure 1, a potential difference equal to their separation on Figure 2 appears between them. The corrosion potential of iron, -0.44 , differs from that of copper, $+0.34$, by 0.78 volts, so if no current flows in the connection the voltmeter will register this difference. If a current is now allowed, electrons flow from the iron (the *anode*) to the copper (the *cathode*); the iron ionizes (that is, it corrodes), following the anodic ionization reaction described above and - if the solution were one containing copper sulphate - copper ions, Cu^{++} , plate out onto the copper following the cathodic reaction



Suppose now that the liquid is not a copper sulphate solution, but just water (Figure 3). Water dissolves oxygen, so unless it is specially de-gassed and protected from air, it contains oxygen in solution. The iron and the copper still dissociate until their corrosion potential-difference is established but now, if the current is allowed to flow, there is no reservoir of copper ions to plate out. The iron still corrodes but the cathodic reaction has changed; it is now the *hydrolysis reaction*



While oxygen can reach the copper, the corrosion reaction continues, creating Fe^{++} ions at the anode and OH^{-} ions at the cathode. They react to form insoluble $\text{Fe}(\text{OH})_2$ which ultimately oxidizes further to $\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$, rust.

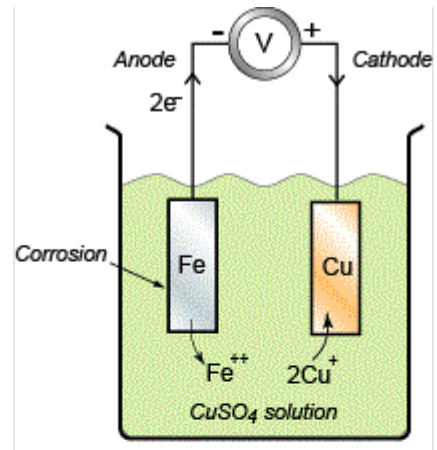


Figure 1. A bi-metal corrosion cell. The corrosion potential is the potential to which the metal falls relative to a hydrogen standard.

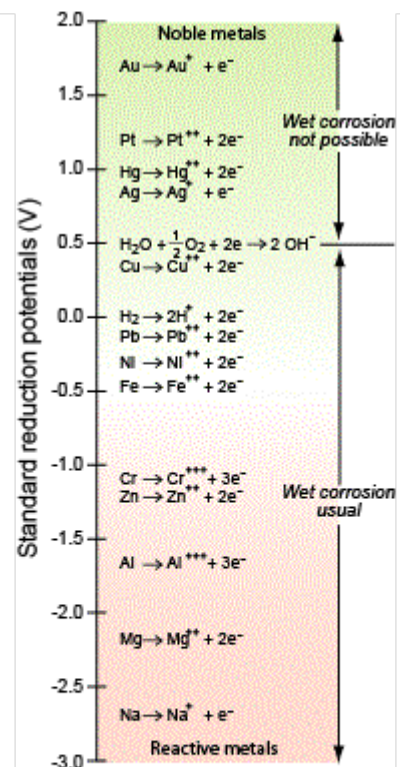


Figure 2. Standard reduction potentials of metals.

Differential aeration corrosion

Thus connecting dissimilar metals in either pure water or water with dissolved salts is a bad thing to do: corrosion cells appear that eat up the metal with the lower (more negative) corrosion potential. Worse news is to come: it is not necessary to have two metals: both anodic and cathodic reactions can take place on the same surface. Figure 4 shows how this happens. Here an iron sample is immersed in water with access to air. The part of the sample nearest the water surface has an easy supply of oxygen; that further away does not. On the remoter part the ionization reaction takes place, corroding the iron, and releasing electrons that flow up the sample to the near-surface part where oxygen is plentiful, where they enable the hydrolysis reaction. The hydrolysis reaction has a corrosion potential of +0.81 volts - it is shown on Figure 2 - and the difference between this and that of iron, -0.44 volts, drives the corrosion. If the sample could be cut in two along the broken line in Figure 4 and a tiny voltmeter inserted, it would register the difference: 1.23 volts.

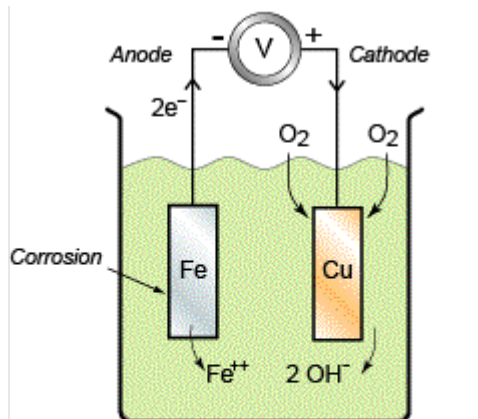


Figure 3. A bi-metal cell containing pure water in which oxygen can dissolve.

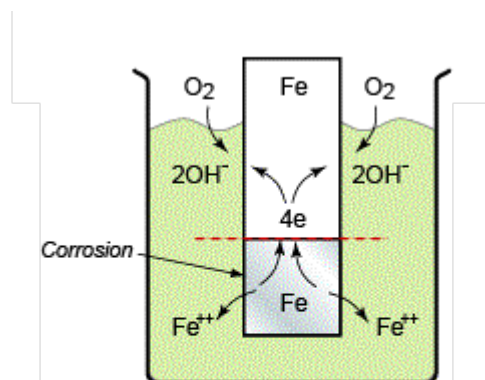


Figure 4. A corrosion cell created by differential access to oxygen.

This differential oxidation corrosion is one of the most usual and most difficult to prevent: where there is water and a region with access to oxygen and one that is starved of it, a cell is set up. Only metals above the hydrolysis reaction potential of +0.81 volts in Figure 2 are immune.

Resistance to electrochemical corrosion is ranked on a 4-point scale from 1 (*Unacceptable*) to 4 (*Excellent resistance*). Notes attached to individual environments give more details.

See also [Durability: acids and alkalis](#).

Further reading

Author	Title	Chapter
Ashby et al	Materials: Engineering, Science, Processing and Design	17
Budinski	Engineering Materials: Properties and Selection	13, 21
Callister	Materials Science and Engineering: An Introduction	17
Shackelford	Introduction to Materials Science for Engineers	14

[Further reference](#)

Environments

Water (fresh)

Where found

Fresh water is ubiquitous: any object: exposure to rain, to washing or to high humidity acquires a film of water containing (unless distilled) dissolved oxygen and, usually, other impurities.

Industrial sectors

Petroleum, food processing, chemical engineering, engineering manufacture, construction, energy conversion, marine engineering, aerospace, bio-engineering

The problem

Causes localized corrosion on iron and non-stainless steels.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Aluminium alloys	All polymers are corrosion free in fresh water, though some absorb up to 5%, causing swelling.	Glass
Stainless steels	PET	Concrete
Galvanized steel	HDPE	Brick
Copper alloys (pipe work and heating systems)	GFRP	Porcelain

Inhibitors

Calcium bicarbonate (Steel, Cast Iron), polyphosphate (Cu, Zn, Al, Fe), calcium hydroxide (Cu, Zn, Fe), sodium silicate (Cu, Zn, Fe), sodium chromate (Cu, Zn, Pb, Fe), potassium dichromate (Mg), sodium nitrite (Monel), benzoic acid (Fe), calcium and zinc metaphosphates (Zn).

Underlying mechanisms

Aqueous corrosion, [electrochemical corrosion](#), [differential aeration corrosion](#)

Water (salt)

Where found

Found in marine environments, both as water and as wind-carried spray. Seawater varies in composition depending on the climate. Body fluids have about the same salinity as the sea.

Industrial sectors

Petroleum, marine engineering, aerospace, bio-engineering

The problem

Salt water has a high conductivity, enabling fast electro-chemical attack.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Copper	All polymers are corrosion free in salt water, though some absorb up to 5%, causing swelling.	Glass
Bronze		PET
Stainless steels	HDPE	Brick
Galvanized steels	GFRP	
Lead		
(Platinum, Gold, Silver)		

Inhibitors

Sodium nitrite (Fe), sodium silicate (Zn), calcium bicarbonate (all metals), amyl stearate (Al), methyl-substituted dithiocarbamates (Fe)

Underlying mechanisms

Electrochemical corrosion, differential aeration corrosion

Soils, acidic and alkali

Where found

Soils differ greatly in composition, moisture content and pH. The single most important property of a soil that determines its corrosive behaviour is its electrical resistivity – a low resistivity means that the water in the soil has high concentration of dissolved ions. A resistivity below 10^9 mΩcm is very corrosive; one with a resistivity above 2×10^{10} mΩcm is only slightly corrosive. The choice of material for use in soil depends on this and on the pH. Acidic (peaty) soils have a low pH; alkali soils (those containing clay or chalk) have a high one.

Industrial sectors

Petroleum, construction, and marine engineering

The problem

Electro-chemical attack over long periods of time, leading to near-surface failure

Preferred materials and coatings

Metals	Polymers	Ceramics and glasses
Steel, bare in high-resistivity soil, coated or with galvanic protection in those with low resistivity.	Most polymers (except PHB, PLA and those that are bio-degradable) corrode only very slowly in soil.	Brick
		Pottery
	HDPE	Glass
	PP	Concrete
	PVC	

Inhibitors

Calcium nitrate is added to concrete to inhibit corrosion of steel reinforcement in soils.

Underlying mechanisms

Electrochemical corrosion, acidic attack, biological attack

Wine

Where found

Wine, the product of fermentation of fruit sugars, is a dilute (10%) solution of ethanol in water, with low levels of SO₂ esters and resins. When exposed to air the ethanol oxidizes to acetic acid. Materials are involved both in the manufacture and in the long-term storage and distribution of wine.

Industrial sectors

Food processing, domestic

The problem

The slightest trace of corrosion products contaminates wine, so the demands on materials both for processing and storage are great.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Stainless steels (Monel) (Hastelloy C)	Polyethylene	Glass

Underlying mechanisms

Acid attack, electrochemical attack

Durability: acids and alkalis

Science note

Acids, alkalis and pH

Pure water, H₂O, dissociates a little to give a hydrogen ion, H⁺, and a hydroxyl ion, OH⁻:



According to the Law of Mass Action,

$$[\text{H}^+].[\text{OH}^-] = \text{constant}$$

In the above, the square brackets mean "molar concentration". In pure water there are equal numbers of the two types of ion, [H⁺] = [OH⁻], and the value of the constant, when measured, is 10⁻¹⁴. Thus the molar concentration of both ion-types is 10⁻⁷. The pH and pOH of the ionized water is defined as

$$\text{pH} = -\log_{10}[\text{H}^+] \text{ and } \text{pOH} = -\log_{10}[\text{OH}^-]$$

So, for pure water, pH = pOH = 7

Acids dissociate in water to give H⁺ ions. Sulphuric acid, one of the commonest of chemicals, is an example:



This pushes up the concentration [H⁺] and, because of the Law of Mass Action (equation), it pulls down the concentration [OH⁻]; weak acids have a pH of 4 – 6; strong ones a pH up to 0. Alkalis do the opposite. Sodium hydroxide, for example, dissociates when dissolved in water, to give OH⁻ ions:



Weak alkalis have a pH of 8 – 10; strong ones a pH up to 13.

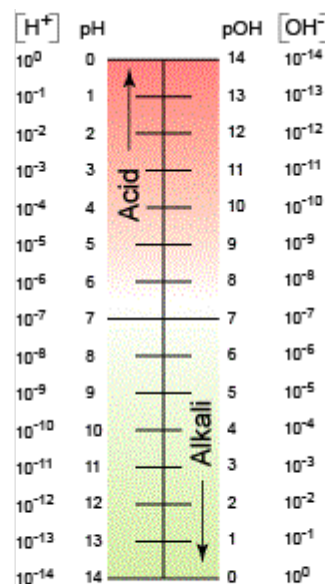


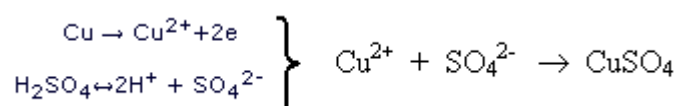
Figure 1. The scales of pH and pOH.

Acid attack

Acids stimulate electrochemical reaction. One half of this is the dissociation reaction of a metal M into a metal ion, M^{z+}, releasing electrons e⁻



In the above, z, an integer of 1, 2, or 3, is the valence of the metal. Acidic environments, with high [H⁺] (and thus low pH) stimulate this reaction; thus a metal such as copper, in sulphuric acid solution, reacts rapidly



Some metals are resistant to attack by some acids because the reaction product, here CuSO₄, forms a protective surface layer; thus lead-lined containers are used to process sulphuric acid because lead sulphate is protective.

Alkali attack

Most metals are immune to attack by alkalis because their hydroxide, formed in the reaction, is protective. There are, however, exceptions, notably aluminium, that forms non-protective aluminium hydroxide, $\text{Al}(\text{OH})_3$.

Resistance to acid and alkali attack is ranked on a 4-point scale from 1 (*Unacceptable*) to 4 (*Excellent resistance*). Notes attached to individual environments give more details.

See also [Durability: water and aqueous environments](#).

Further reading

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Ashby et al	Materials: Engineering, Science, Processing and Design	17
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[Further reference details](#)

Environments

Acetic acid (10%), CH₃COOH

Where found

Acetic acid is an organic acid made by the oxidation of ethanol. It is used in the production of plastics, dyes, insecticides and other chemicals. Dilute acetic acid (vinegar) is used in cooking.

Industrial sectors

Chemical engineering, food processing, domestic

The problem

Acetic acid can attack any metal surface it is in contact with. It can also affect polymers to a lesser extent.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Aluminium	HDPE	Glass
Stainless steel	PTFE	(Porcelain)
Nickel		(Graphite)
Nickel alloys		
Titanium		
(Monel)		

Inhibitors

Thiourea, arsenic oxide, sodium arsenate (all for Fe)

Underlying mechanisms

Acid attack

Acetic acid (glacial), CH₃COOH

Where found

Glacial acetic acid (containing <1% water) is used for production of paints, inks, acetic anhydride and also as a solvent (particularly for PET).

Industrial sectors

Food processing, chemical engineering

The problem

Glacial acetic acid is much more corrosive than dilute acetic acid (vinegar). It is regarded as strongly corrosive and will naturally attack any metal it comes into contact with. It is also flammable.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Aluminium (not when hot)	HDPE	Glass
Stainless steel	PTFE	Graphite
Nickel		
Nickel alloys		
(Monel)		
(Alloy 20 (40Fe, 35Ni, 20Cr, 4Cu))		

Inhibitors

Thiourea, arsenic oxide, sodium arsenate (all for Fe)

Underlying mechanisms

Acid attack

Citric acid (10%), $\text{HOOCCH}_2\text{COOH(OH)CH}_2\text{COOH}$

Where found

Citric acid is the acid found in citrus fruits (lemons, grapefruit etc.) that gives them a sour, acidic taste. It is used to flavour many foodstuffs so any contamination by corrosion is unacceptable.

Industrial sectors

Food processing, domestic

The problem

Citric acid is not highly corrosive and is often stored in ordinary food cans. It does, however, attack aluminium.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Stainless steel	PE	Glass
Tin	PET	Graphite
(Hastelloy C)	PS	
	PP	
	PTFE	

Inhibitors

Thiourea, arsenic oxide, sodium arsenate, cadmium salts (all for Fe).

Underlying mechanisms

Acid attack

Hydrochloric acid (10%), HCl

Where found

Hydrochloric acid is used as a chemical intermediate, for ore reduction, for pickling steel, in acidizing oil wells and in other industrial processes. In dilute form it is a component of household cleaners.

Industrial sectors

Chemical engineering, engineering manufacture

The problem

Hydrochloric acid is the most difficult common acid to contain and transport. It is a strong acid and reacts with most metals at ambient temperatures.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Copper	HDPE	Glass
Nickel and nickel alloys	PP	
Titanium	GFRP	
(Monel)	Rubber	
(Molybdenum)		
(Tantalum)		
(Zirconium)		
(Platinum, Gold, Silver)		

Inhibitors

Ethylaniline, mercaptobenzotriazole, pyridine & phenylhydrazine, ethylene oxide (all used for Fe), phenylacridine (Al), naphthoquinone (Al), thiourea (Al), chromic acid (Ti), copper sulphate (Ti).

Underlying mechanisms

Acid attack; stress corrosion cracking.

Hydrochloric acid (36%), HCl

Where found

Hydrochloric acid is used as a chemical intermediate (in the production of PVC, for instance), for ore reduction, for pickling steel, in acidizing oil wells and in other industrial processes.

Industrial sectors

Chemical engineering, domestic

The problem

Concentrated hydrochloric acid is highly corrosive. It is a strong acid that reacts with most metals and some polymers at ambient temperatures. It is also toxic.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
(Molybdenum)	HDPE	Glass
(Tantalum)	PET	Graphite
(Zirconium)	Rubber	
(Platinum, Gold, Silver)		

Inhibitors

Ethylaniline, mercaptobenzotriazole, pyridine & phenylhydrazine, ethylene oxide (all used for Fe), phenylacridine (Al), naphthoquinone (Al), thiourea (Al), chromic acid (Ti), copper sulphate (Ti).

Underlying mechanisms

Acid attack; stress corrosion cracking.

Hydrofluoric acid (40%), HF

Where found

Hydrofluoric acid is used for the etching of glass, synthesis of fluorocarbon polymers, aluminium refining, as an etchant for silicon-based semi-conductors and to make UF_6 for uranium isotope separation.

Industrial sectors

Nuclear power, chemical engineering

The problem

Hydrofluoric acid is extremely corrosive and toxic.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Lead	PTFE	Graphite
Copper	Fluorocarbon polymers	
Stainless Steel	Rubber	
Carbon Steels		
(Monel)		
(Hastelloy C)		
(Platinum, Gold, Silver)		

Inhibitors

Thiourea, arsenic oxide, sodium arsenate (all for Fe)

Underlying mechanisms

Acid attack; stress corrosion cracking.

Nitric acid (10%), HNO₃

Where found

Nitric acid is used in the production of fertilizers, dyes, drugs, and explosives.

Industrial sectors

Chemical engineering

The problem

Nitric acid, an oxidizing acid, is very corrosive and toxic.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Stainless steel	PTFE	Glass
Titanium	PVC	Graphite
(14.5% Silicon cast iron)	Phenolics	
(Alloy 20 (40Fe, 35Ni, 20Cr, 4Cu))	PE-CTFE	

Inhibitors

Thiourea, arsenic oxide, sodium arsenate (all for Fe), hexamethylene tetramine (Al), alkali chromate (Al)

Underlying mechanisms

Acid attack; stress corrosion cracking.

Nitric acid (70%), HNO₃

Where found

Nitric acid is used industrially in synthesis of polymers (e. g. Nylon), TNT manufacture, and making fertilizers.

Industrial sectors

Chemical engineering

The problem

Nitric acid, an oxidizing acid, is very corrosive and toxic.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Stainless steel	PTFE	Glass
Titanium	PE-CTFE	
(14.5% Silicon cast iron)	PVC	
(Alloy 20 (40Fe, 35Ni, 20Cr, 4Cu))	Phenolics	
(Zirconium)		
(Tantalum)		
(Platinum, Gold)		

Inhibitors

Thiourea, arsenic oxide, sodium arsenate (all for Fe)

Underlying mechanisms

Acid attack; stress corrosion cracking.

Phosphoric acid (10%), H₃PO₄

Where found

Dilute phosphoric acid is added to certain food and beverages and used as a dental etchant and other pharmaceuticals.

Industrial sectors

Chemical engineering, medical, food processing

The problem

Phosphoric acid is a highly corrosive reducing agent.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Stainless steel	PTFE	Glass
Lead	GFRP	Graphite
(Hastelloy C)	(FEP)	
(14.5% Silicon cast iron)		
(Alloy 20 (40Fe, 35Ni, 20Cr, 4Cu))		
(Zirconium)		
(Tantalum)		
(Platinum, Gold)		

Inhibitors

Sodium iodide (all metals), alkali or sodium chromates (Al)

Underlying mechanisms

Acid attack.

Phosphoric acid (85%), H₃PO₄

Where found

Phosphoric acid is a strong acid used in the production of fertilizers and pharmaceuticals, and for removal of rust from iron surfaces (pickling).

Industrial sectors

Chemical engineering, medical, food processing

The problem

Phosphoric acid is a highly corrosive reducing agent.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Stainless steel	PTFE	Borosilicate glass
(14.5% Silicon cast iron)	GFRP	
(Alloy 20 (40Fe, 35Ni, 20Cr, 4Cu))	(FEP)	
(Tantalum)	(Vinyl ester)	
(Platinum, Gold)		

Inhibitors

Sodium iodide (all metals), alkali or sodium chromates (Al), dodecylamine with potassium iodide

Underlying mechanisms

Acid attack

Sulphuric acid (10%), H₂SO₄

Where found

Sulphuric acid, of central importance in chemical engineering, is used in making fertilizers, chemicals, paints, and in petrol refining. It is a component of "acid rain".

Industrial sectors

Chemical engineering, petroleum engineering.

The problem

Sulphuric acid, an oxidizing acid, is highly corrosive and toxic.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Stainless steel	PET	Glass
Copper	PTFE	Graphite
Nickel based alloys	PE-CTFE	
Lead	Phenolics	
Tungsten		
(14.5% Silicon cast iron)		
(Alloy 20 (40Fe, 35Ni, 20Cr, 4Cu))		
(Zirconium)		
(Tantalum)		
(Platinum, Gold, Silver)		

Inhibitors

Phenylacridine (Fe), sodium chromate (Al), benzyl thiocyanate (Cu & Brass), hydrated calcium sulphate (Fe), aromatic amines (Fe), chromic acid (Ti), copper sulphate (Ti)

Underlying mechanisms

Acid attack; stress corrosion cracking.

Sulphuric acid (70%), H₂SO₄

Where found

Sulphuric acid is used industrially for processing metal ores, producing fertilizers, oil refinement, processing wastewater, and synthesis of sulphur-containing chemicals.

Industrial sectors

Chemical engineering, petroleum engineering.

The problem

Sulphuric acid, an oxidizing acid, is highly corrosive and toxic. It is a dehydrating agent. Heat from exothermic reactions can be sufficient to boil unreacted acid.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Steel	PTFE	Glass
Stainless steel		Graphite
Lead		
(14.5% Silicon cast iron)		
(Alloy 20 (40Fe, 35Ni, 20Cr, 4Cu))		
(Zirconium)		
(Tantalum)		
(Platinum, Gold)		

Inhibitors

Phenylacridine (Fe), sodium chromate (Al), arsenic (Fe), boron trifluoride (Fe), chromic acid (Ti), copper sulphate (Ti).

Underlying mechanisms

Acid attack; stress corrosion cracking.

Sodium hydroxide (10%) (caustic soda), NaOH

Where found

Sodium hydroxide of this concentration is found in some household cleaners, the making of soap, and in the cleaning of certain food products.

Industrial sectors

Chemical engineering, domestic, food processing

The problem

The strong alkalis NaOH, KOH (potassium hydroxide), and NH₄OH (ammonium hydroxide) are all corrosive and toxic. Vapours are dangerous.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Nickel and its alloys	PVC	Glass
Stainless steels	LDPE	Graphite
Lead	HDPE	
Magnesium	PTFE	
	(PE-CTFE)	

Inhibitors

Alkali silicates, potassium permanganate, glucose (all for Al)

Underlying mechanisms

Basic attack; stress corrosion cracking (stainless steels).

Sodium hydroxide (60%) (caustic soda), NaOH

Where found

Sodium hydroxide of this concentration is found in drain cleaners as a 50% solution, is used to produce alumina, paper and bio diesel, and is used to clean and etch aluminium.

Industrial sectors

Chemical engineering, domestic, petroleum, engineering manufacture

The problem

The strong alkalis NaOH, KOH (potassium hydroxide), and NH₄OH (ammonium hydroxide) are all corrosive and toxic. Vapours are dangerous.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Nickel and its alloys	PVC	Glass
Stainless steels	LDPE	Graphite
	HDPE	
	PTFE	
	(PE-CTFE)	

Underlying mechanisms

Basic attack; stress corrosion cracking.

Durability: organic solvents and other organic fluids

Science note

Organic solvents and fluids

Organic liquids are ubiquitous: we depend on them as fuels and lubricants, for cooking, for removing stains, as face-cream, as nail varnish, and much more. Any material in service will encounter them. Ceramics and glasses are largely immune to them, and many metals and some polymers can tolerate some organic liquids without problems.

Resistance to organic solvents and other organic fluids, ranked here on a 4-point scale from 1 (*Unacceptable*) to 4 (*Excellent*) is measured by weight or section loss (metals) or by swelling, solution and property degradation (polymers and elastomers). The ranking gives only the broadest indication of susceptibility. The notes attached to the environments give more details.

Polarity and proticity

There are two things to know about an organic liquid.

- Is it non-polar or polar? Simple hydrocarbons (like benzene, C₆H₆) and symmetrically halogenated solvents (like carbon tetrachloride, CCl₄) carry not dipole moment. Hydrocarbons with polar side groups like acetone CH₃COCH₃ and acetaldehyde CH₃CHO) carry a dipole moment.
- Is it aprotic (water insoluble) or protic (water soluble)? Toluene C₆H₅CH₃, like benzene C₆H₆, is aprotic. Alcohols like ethanol, CH₃CH₂OH, and organic acids such as acetic acid CH₃COOH are protic.

Why are these important?

Metal corrosion in organic fluids

Metals are immune to corrosion by aprotic organic fluids but the same is not true of those that are protic because they contain free H⁺ ions. Corrosion rates in protic organic fluids can be high: carbon steels, for example, corrode in ethanol, methanol, and acetic acids.

Polymer and elastomer degradation in organic fluids

Certain polymers are degraded by certain organic solvents. The nearest that this can be made scientific is via what are called *solubility parameters*. Polymer chains are bonded strongly (covalent bonding) along their length, but only weakly (van der Waals bonding) between chains. To enter a polymer, the solvent, like a virus, must trick these bonds into allowing them in. Thus polar solvents dissolve in polar polymers (nylons, for example, are polar). Non-polar solvents tend to dissolve in non-polar polymers (the phrase "like dissolves like" sums it up). Once in – like viruses – they do things, mostly bad, a few, good.

The bad: aggressive solvents cause discoloration, reduce strength, induce brittleness, and trigger crazing (the whitening of the polymer because of many tiny crack-like expansion cavities). The good: certain organic solvents act as plasticizers, reducing the glass temperature but not the strength, converting a rigid polymer into a flexible, leather-like material. Artificial leather – plasticized PVC – is an example. Many plasticizers are phthalates but increasing concern for their potential toxicity generates pressure to use alternatives. Phthalates are increasingly being replaced by biochemical plasticizers – vegetable oils such as soy bean oil or linseed oil – even though these are more expensive.

Further reading

Author	Title	Chapter
Ashby et al	Materials: Engineering, Science, Processing and Design	17
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Environments

Amyl acetate (banana oil), $\text{CH}_3\text{COO}(\text{CH}_2)_4\text{CH}_3$

Where found

Amyl acetate is used in the food industry to provide a scent similar to bananas and apples. Used as a solvent for paints and lacquers, as well as in the preparation of penicillin.

Industrial sectors

Food processing, domestic, construction

The problem

Amyl acetate is flammable. It is an organic solvent that dissolves, and thus attacks, polymers such as PMMA, nylon, neoprene and buna rubber. It contains some acetic acid, making it corrosive to carbon steel.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Stainless steel	PTFE	Glass
Aluminium	HDPE	
Brass	PET	
(Hastelloy C)	(EPDM)	
(Alloy 20 (40Fe, 35Ni, 20Cr, 4Cu))		

Underlying mechanisms

Organic solution

Benzene, C₆H₆

Where found

Benzene is used as an industrial solvent, as well as in the synthesis of plastics, rubbers, dyes, and certain drugs. It is also found in tobacco smoke.

Industrial sectors

Petroleum, chemical engineering, domestic, engineering manufacture

The problem

Benzene is a highly flammable organic solvent. It is carcinogenic. It attacks some polymers.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Carbon steel	PTFE	Glass
Stainless steel		Graphite
Aluminium		
Brass		

Inhibitors

Anthraquinone (Cu & Brass).

Underlying mechanisms

Organic solution

Carbon tetrachloride (tetrachloromethane), CCl₄

Where found

Carbon tetrachloride is a chemical used principally to manufacture refrigerants, although it has also found uses as a dry-cleaning solvent as well as a pesticide (now banned in the US).

Industrial sectors

Chemical engineering, domestic

The problem

Carbon tetrachloride is a powerful organic solvent. It is toxic, carcinogenic and a "greenhouse" gas. When moist it becomes breaks down to HCl, causing corrosion of metals.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Carbon steel	POM	Glass
Stainless steel	PTFE	Graphite
Aluminium	Rubber	
(Hastelloy C)		
(Monel)		
(Platinum, Gold, Silver)		

Inhibitors

Formamide (Al), aniline (Fe, Sn, Brass, Monel & Pb), mesityl oxide (Sn).

Underlying mechanisms

Organic solution, acid attack

Chloroform (trichloromethane), CHCl₃

Where found

Chloroform is most commonly used today as a refrigerant (R-22). It used to synthesize chlorinated polymers and as a solvent for paints and dyes. It is an anaesthetic, once used medically but now supplanted by those that are less toxic.

Industrial sectors

Domestic, medical, chemical engineering, construction

The problem

Chloroform is an organic solvent that attacks polymers such as nylon, PMMA and neoprene. When moist, it decomposes to form a weak HCl, becoming corrosive to carbon steel and aluminium.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Stainless steel	PTFE	Glass
Carbon steel	HDPE	
Brass	PET	
(Monel)		
(Hastelloy C)		
(Alloy 20 (40Fe, 35Ni, 20Cr, 4Cu))		

Underlying mechanisms

Organic solution, Acid attack

Crude oil

Where found

Refined petroleum is not corrosive to metals, but crude oil usually contains saline water, sulphur compounds, and other impurities, some acidic.

Industrial sectors

Petroleum, engineering, marine engineering, energy conversion

The problem

Crude oil is flammable. It is corrosive to many materials because of wide range of contaminants. The corrosion rate of steel – the most widely used material for pipe work and storage – shows a sudden increase when the salt water content of the oil exceeds a critical level (the “corrosion rate break”) of between 3 and 10%, depending on the grade of oil. Crude oils vary in their sulphur content – those with high sulphur are more corrosive.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Carbon steel	HDPE	Glass
Aluminium	PTFE	Porcelain
Stainless steels	Epoxies (Polyimides)	Enamelled metal

Underlying mechanisms

Organic solution; sulphurisation, acid attack

Diesel oil (petrodiesel)

Where found

Diesel oil is a specific fractional distillate of crude oil. It is the primary fuel for truck, shipping, and non-electric and diesel-electric rail transport. Its use for car propulsion is increasing. Diesel oil acts both as fuel and as lubricant in the engine.

Industrial sectors

Petroleum, engineering manufacture, transport

The problem

The corrosive properties of diesel oil depend on its source, on temperature, and on time. Sour diesel oil contains sulphur and is acidic; recent legislation has required producers to produce ultra-low sulphur diesel to minimize toxic emissions. Temperatures above 150°C will cause additives in diesel to breakdown giving corrosive by-products and damaging its lubricating properties. Some polymers (Neoprene, styrene-butadiene rubber, natural rubber, EVA, EPDM) are attacked by diesel oil.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Carbon steel	HDPE	Glass
Stainless steel	PP	
Brass	PTFE	
Copper	Buna (nitrile) rubber	
Aluminium	(Viton)	
(Monel)	GFRP	

Inhibitors

PTFE suspension (all metals), chlorinated hydrocarbons (all metals), poly-hydroxybenzophenone (Cu)

Underlying mechanisms

Organic solution, sulphurisation

Lubricating oil

Where found

Oil is used as a lubricant in most metal systems with moving parts. Typically, these are mineral oils, and frequently contain sulphur. Low sulphur synthetic oils can also be produced. Lubricating oil is less corrosive than petroleum and diesel oil because it is based on hydrocarbons with higher molecular weight.

Industrial sectors

Petroleum, engineering manufacture, energy conversion, marine engineering, aerospace

The problem

Lubricating oil is flammable and toxic. Corrosion of metals in lubricating oil is slow, though it can be a problem with copper.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Stainless steel	HDPE	Glass
Carbon steel	PP	
Aluminium	PTFE	
	Rubber	

Inhibitors

PTFE suspension (all metals), chlorinated hydrocarbons organozinc compound selected such as zinc dithiophosphate and zinc dithiocarbamate (all metals), poly-hydroxybenzophenone (Cu).

Underlying mechanisms

Sulphurisation

Paraffin oil (kerosene)

Where found

Paraffin is used as aviation fuel, as well as being commonly used for heating and lighting on a domestic level. It is used to store highly reactive metals to isolate them from oxygen.

Industrial sectors

Petroleum, engineering manufacture, transport

The problem

Paraffin oil is highly flammable. It is an organic solvent. Some kerosenes contain sulphur, which in the presence of water or condensation becomes an acid solution leading to corrosion. The combustion products can be corrosive to metals.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Carbon steel	HDPE	Glass
Stainless steel	PP	
Aluminium	PTFE	
(Monel)	GFRP	

Inhibitors

PTFE suspension (all metals), chlorinated hydrocarbons (all metals), poly-hydroxybenzophenone (Cu)

Underlying mechanisms

Organic solution, sulphurisation

Petroleum (gasoline)

Where found

Petroleum is a volatile distillate of crude oil. It is used mainly to power engines, for cars, light aircraft, and agricultural equipment. It often contains additives such as lead, ethanol, or dyes.

Industrial sectors

Petroleum, engineering manufacture, construction, energy conversion, marine engineering, aerospace

The problem

Gasoline is extremely flammable. It is an organic solvent that attacks nylon, neoprene and buna rubber. The presence of sulphur in gasoline can cause corrosion in internal combustion engines – copper is particularly susceptible to sulphur attack.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Carbon steel	PTFE	Glass
Stainless steel	HDPE	
Brass	PP	
Aluminium	GFRP	
(Hastelloy C)		
(Alloy 20 (40Fe, 35Ni, 20Cr, 4Cu))		

Inhibitors

PTFE suspension (all metals), chlorinated hydrocarbons (all metals)

Underlying mechanisms

Organic solution, sulphurisation

Silicone oils, $((\text{CH}_3)_2\text{SiO})_n$

Where found

Silicone oils are synthetic silicon-based polymers. They are exceptionally stable and inert. They are used as brake and hydraulic fluids, vacuum pump oils and as lubricants both for metals and for textile threads during spinning, sewing, and weaving of fabrics.

Industrial sectors

Mechanical engineering, textile fabrication, domestic

The problem

The low vapour pressure, low flammability and chemical inertness of silicone fluids makes them non-aggressive to almost all materials. They interact mildly with silicone elastomers and with PMMA and POM.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Carbon steel	HDPE	Glass
Aluminium	PP	
	PET	

Underlying mechanisms

Organic solvent attack

Toluene (methyl benzene), C₆H₅CH₃

Where found

Toluene is used in applications where benzene cannot be used because of its carcinogenic properties. These are mainly as a solvent for paints, dyes, silicone sealant, rubber, printing ink, glues, and lacquers. It is used to make TNT.

Industrial sectors

Domestic, construction, aerospace

The problem

Toluene is flammable. It is a powerful organic solvent that attacks some polymers but does not corrode metals.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Carbon steel	PTFE	Glass
Aluminium		
Stainless steel		
Brass		
(Monel)		

Underlying mechanisms

Organic solution

Turpentine, C₁₀H₁₆

Where found

Turpentine is a common household chemical used as a solvent for oil and paints. It is used to produce aromatic chemicals and as a disinfectant.

Industrial sectors

Domestic, chemical engineering

The problem

Turpentine is flammable. It is a powerful organic solvent that attacks some polymers but does not corrode metals.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Carbon steel	PPCO	Glass
Aluminium	PTFE	
Stainless steel	Nylon	
Brass		
(Monel)		

Underlying mechanisms

Organic solution

Vegetable oils

Where found

Vegetable oils are derived from olive, peanut, maize, sunflower, rape, and other seed and nut crops. They are widely used in the preparation of foods. They are the basis of bio-fuels.

Industrial sectors

Petroleum, food processing.

The problem

Vegetable oils are flammable. They can contain sulphur, corrosive to copper.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Aluminium	HDPE	Glass
Carbon steel	PP	
Stainless steel	PET	

Inhibitors

Poly-hydroxybenzophenone (Cu), succinic acid (Cu & Brass)

Underlying mechanisms

Sulphurisation

White spirit (Stottard solvent)

Where found

White spirit is clear, paraffin-derived solvent made up of hydrocarbons with the chain length C₇ to C₁₂. It is used as a thinning agent for paints, as an extraction solvent, and as a cleaning and degreasing agent.

Industrial sectors

Mechanical engineering, chemical engineering and domestic

The problem

White spirit is a volatile, toxic, highly flammable fluid. It is damaging to most elastomers, including EVA, butyl and styrene-butadiene rubber. Metals are not corroded by white spirit.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Aluminium	HDPE	Glass
Carbon steel	PP	
Stainless steel		

Underlying mechanisms

Organic solvent attack

Acetaldehyde (Ethanal), CH₃CHO

Where found

Acetaldehyde is a feedstock for many organic synthesis processes. It occurs naturally in fruit, coffee, bread, and most plants. The liver converts ethanol to acetaldehyde, the accumulation of which is the cause of hangovers.

Industrial sectors

Petroleum, food processing, chemical engineering, energy conversion, industrial manufacture

The problem

Acetaldehyde is flammable and toxic. It is an organic solvent and is mildly corrosive to carbon steel, zinc, copper, and brass, partly because of the ease with which it oxidizes to acetic acid. It attacks some polymers (e.g. neoprene) severely.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Stainless steel	PTFE	Glass
Nickel alloys	HDPE	
Titanium	PET	
(Monel)		
(Hastelloy C)		
(Zirconium)		

Underlying mechanisms

Acid attack, organic solution

Acetone (propanone) CH₃COCH₃

Where found

Acetone is the simplest of ketones. It is widely used as a degreasing agent and a solvent, and as a thinning agent for polyester resins and other synthetic paints (commonly nail varnish), a cleaning agent, and as an additive in automobile fuels. It is used in the manufacture of plastics, drugs, fibres, and other chemicals.

Industrial sectors

Construction, domestic

The problem

Metals are not attacked by acetone. However it dissolves or attacks some polymers and synthetic fibres, notably ABS, PC, PMMA and some nylons polyesters, epoxies and elastomers. It is highly flammable and is classed as a volatile organic compound (VOC), requiring that precautions are taken with its use.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Aluminium	PTFE	Glass
Carbons steel	HDPE	Graphite
Stainless steel	PP copolymer (PPCO)	

Underlying mechanisms

Organic solution

Ethyl alcohol (Ethanol), CH₃CH₂OH

Where found

Ethanol is made by fermentation, and thus in alcoholic beverages. It is used medically as a solvent for disinfectants, and for cleaning wounds before dressing them. It is used industrially as a solvent, a dehydrating agent, and as a fuel for "eco-friendly" cars.

Industrial sectors

Petroleum, food processing, engineering manufacture, domestic

The problem

Ethanol is highly flammable. If allowed to absorb water it attacks metals by electro-chemical corrosion. Much ethanol is acidic (pH as low as 2) because of contamination with acetic acid or SO₂ used in its preparation. Ethanol attacks certain plastics and rubbers including those used in standard cars. Its introduction as a bio-fuel addition to gasoline can create corrosion and degradation problems in conventional fuel tanks and lines.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Steel,	PTFE	Glass
Stainless steel	HDPE	
Copper	PP	
	GFRP	

Inhibitors

Potassium dichromate, alkali carbonates or lactates (Al), benzoic acid (Cu & Brass), alkaline metal sulphides (Mg), ethylamine (Fe), ammonium carbonate with ammonium hydroxide (Fe)

Underlying mechanisms

Electrochemical corrosion, acid attack, organic solution

Ethylene glycol, HOCHCH₂CH₂CHOH

Where found

Ethylene glycol is the main component of automotive antifreeze and in de-icing fluid for windscreens and aircraft. It is used to inhibit deposits in natural gas pipelines, in the manufacture of PET and polyester fibres and as a medium in the low-temperature preservation of biological tissue.

Industrial sectors

Chemical engineering, petroleum engineering, domestic, medical

The problem

Ethylene glycol is flammable and toxic. It attacks certain plastics and rubbers.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Carbon steel	PTFE	Glass
Aluminium	HDPE	
Copper	PP	

Inhibitors

Sodium tungstate/molybdate/nitrate (Al), alkali borates/phosphates (Cu, Fe & Brass), trisodium phosphate (Fe), guanidine (Fe)

Underlying mechanisms

Electrochemical corrosion, organic solution

Formaldehyde (Methanal), CH₂O

Where found

Formaldehyde is used as a disinfectant in medical applications. It is used industrially to make many resins (including melamine resin and phenol formaldehyde resin) and glues, including those used in plywood. It is found in car exhausts and tobacco smoke. It is the basis of embalming fluids.

Industrial sectors

Medical, chemical engineering

The problem

Formaldehyde is an irritant, and, with prolonged exposure, carcinogenic. It is a reducing agent. Aluminium alloys are attacked by formaldehyde above 60°C.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Stainless steel	PTFE	Glass
(Monel)	HDPE	GFRP
(Hastelloy C)	PET	
	POM	
	Nitrile or butyl rubber	

Underlying mechanisms

Organic solution

Glycerol (Glycerine), HOCH₂CH₂CH₂(OH)CH₂OH

Where found

Glycerol is a sugar alcohol used as a sweetener, preservative and humectant (a desiccating agent) in foodstuffs. It is used to manufacture polyols and polyurethane foam. It is also used to store enzymatic solutions below zero degrees Celsius and is found in many beauty products, cough syrups, soaps, and in de-icing fluid.

Industrial sectors

Food processing, domestic

The problem

Few materials are affected by glycerine, which is used as a corrosion inhibitor.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Stainless steel	PTFE	Glass
Aluminium	HDPE	Graphite
	PET	

Inhibitors

Alkaline metal sulphides (Mg)

Underlying mechanisms

Organic solution, electrochemical corrosion

Methyl alcohol (Methanol), CH₃OH

Where found

Methanol is used in glass cleaners, stains, dyes, inks, antifreeze, solvents, fuel additives, and as an extractant for oil. It is also used as a high-energy fuel for cars, aircraft, and rockets, and is a possible fuel for fuel cells.

Industrial sectors

Petroleum, domestic, chemical engineering, aerospace, energy conversion

The problem

Methanol is highly flammable and poisonous. It is mildly acidic, corroding some metals, particularly aluminium, and it is generally more corrosive to metals than ethanol. It attacks certain plastics and rubbers. Its introduction as a bio-fuel addition to gasoline can create corrosion and degradation problems in conventional fuel tanks and lines.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Steel	PTFE	Glass
Stainless steel	HDPE	
Lead	PP	
(Monel)		

Inhibitors

Sodium chlorate with sodium nitrate (Al), alkaline metal sulphides (Mg), neutralized stearic acid (Mg), Polyvinylimidazole (Cu).

Underlying mechanisms

Organic solution, acid attack

Durability: gas attack – oxygen, halogens, sulphur dioxide

Science note

Attack by gasses

Rates of attack by gasses are measured in the way sketched in Figure 1: a thin sheet of the material (to give a lot of surface) is held at temperature T for an increasing time t , and the gain or loss in weight, Δm , is measured. If the reaction product adheres to the material, the sample gains weight in a way that is either linear ($\Delta m \propto t$) or parabolic ($\Delta m \propto t^{1/2}$) in time, t ; if instead the reaction product is volatile, the sample loses weight linearly with time ($\Delta m \propto -t$), as in Figure 2. Either way, damage accumulates. Resistance to gas attack is ranked on a 4-point scale from 1 (*Unacceptable*) to 4 (*Excellent resistance*). Notes attached to individual environments give more details.

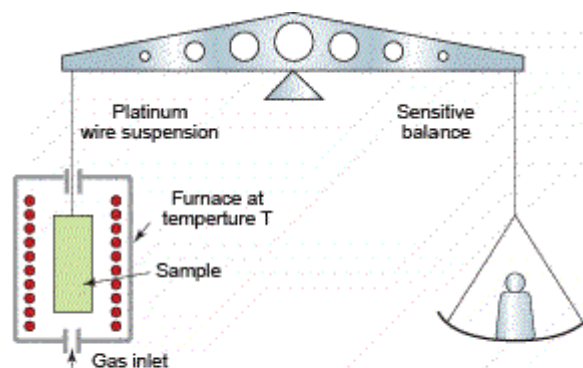
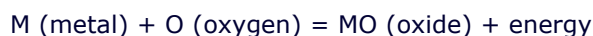


Figure 1. Measuring rates of attack by gasses.

Oxygen attack

The most stable state of most elements is as an oxide of some sort. For this reason, the earth's crust is almost entirely made of simple or complex oxides: silicates like granite, aluminates like basalt and carbonates like limestone. Techniques of thermo-chemistry, electro-chemistry, and synthesis give most of the materials we use in engineering design, but they are not, in general, oxides. From the moment they are made they start to re-oxidize, some extremely slowly, others more quickly; and the hotter they are, the faster they oxidize.

The rate of oxidation of most metals at room temperature is too slow to be an engineering problem; indeed, it can be beneficial in protecting metals from corrosion of other sorts. But heat them up and the rate of oxidation increases, bringing problems. The driving force for a material to oxidize is its *free energy of oxidation* – the energy released when it reacts with oxygen, but a big driving force does not necessarily mean rapid oxidation. The rate of oxidation is determined by the *kinetics* (rate) of the oxidation reaction, and that has to do with the nature of the oxide. When any metal (with the exception of gold, platinum, and a few others that are even more expensive) is exposed to air, an ultra-thin surface film of oxide forms on it immediately, following the oxidation reaction:



The film now coats the surface, separating the metal beneath from the oxygen. If the reaction is to go further, oxygen must get through the film.

The weight-gain shown in Figure 2 reveals two different types of behaviour. For some metals the weight gain is linear, and this implies that the oxidation is progressing at a constant rate:

$$\frac{dm}{dt} = k_l \text{ giving } \Delta m = k_l t$$

Where k_l is the *linear kinetic constant*

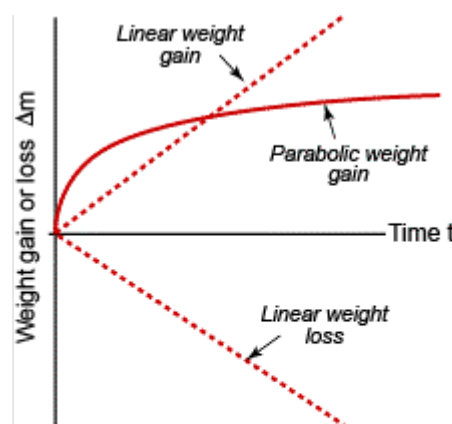


Figure 2. Corrosion rates: linear gain, parabolic gain, and linear loss.

This is because the oxide film cracks (and, when thick, spalls off) and does not protect the underlying metal. Some metals behave better than this. The film that develops on their surfaces is compact, coherent, and strongly bonded to the metal. For these the weight gain is parabolic, slowing up with time, and this implies an oxidation rate with the form:

$$\frac{d(\Delta m)}{dt} = \frac{k_p}{\Delta m} \text{ giving } \Delta m^2 = k_p t$$

In the above, k_p is the *parabolic kinetic constant*. The film, once formed, separates the metal from the oxygen. To react further, either oxygen atoms must diffuse inward through the film to reach the metal or metal atoms must diffuse outward through the film to reach the oxygen. The driving force is the free energy of oxidation, but the rate of oxidation is limited by the rate of diffusion, and the thicker the film, the longer this takes.

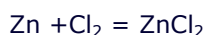
Aluminium, titanium, chromium, and because of this, stainless steels and nickel-based superalloys (which contain up to 20% chromium) have extremely protective oxides. The films can be artificially thickened by *anodizing* – an electro-chemical process for increasing their protective power (see the Process record for *Anodizing*).

Polymers, too, oxidize, but in a more spectacular way. See [Durability: built environments](#) for details.

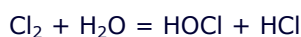
Chlorine attack

Chlorine, Cl₂, made by the electrolysis of sodium chloride solution, is a powerful oxidizing agent. It is widely used as a bleach, in the production of insecticides, and to purify water supplies. Chlorine is an intermediary in the production of PVC, chloroform and other polymers, paints and chemicals, in paper production.

Chlorine gas can react with many metals to give metal chlorides:



Aqueous solutions of chlorine, catalyzed by sunlight, break down to give hydrochloric acid:



This leads to acid attack of metals, concrete and some polymers.

Fluorine attack

Fluorine, F₂, like chlorine, is a powerful oxidizing agent, essential as an etchant in the production of semiconductors, displays, and in MEMS manufacture. It is an intermediary in the manufacture of fluorocarbons (e. g. PTFE, Teflon) and in the extraction of uranium. Fluorine is highly reactive, sufficiently so that many organic materials and some metals ignite spontaneously in its presence:



Selecting materials to handle fluorine requires great care.

Sulphur dioxide attack

Sulphur dioxide, SO₂, made by burning sulphur or by heating sulphide ores such as FeS₂ or ZnS, is a strong reducing agent. It is widely used as a preservative for dried fruit, as an antioxidant in wine-making, as a bleach, and as a precursor in making sulphuric acid. It is one of the pollutants from coal-fired power stations responsible for acid rain. In contact with water it is hydrolyzed to sulphurous acid:



Sunlight can catalyze this reaction further to give sulphuric acid, H₂SO₄. Both acids corrode metals, damage concrete, and can attack some polymers.

Resistance to attack by halogens, oxygen and sulphur dioxide is ranked on a 4-point scale from 1 (*Unacceptable*) to 4 (*Excellent resistance*). Notes attached to individual environments give more details.

Further reading

Author	Title	Chapter
Ashby et al	Materials: Engineering, Science, Processing and Design	17
Ashby & Jones	Engineering Materials Vol 1 & 2	Vol. 1, Chap. 24, 25
Askeland	The Science and Engineering of Materials	23
Budinski	Engineering Materials: Properties and Selection	13, 21
Shackelford	Introduction to Materials Science for Engineers	14

[Further reference details](#)

Environments

Chlorine, Cl₂

Where found

Chlorine is used to make common polymers and textiles, solvents, dyestuffs, disinfectants, fertilizers, for metal degreasing, and to purify water. It forms acid rain if released into the atmosphere.

Industrial sectors

Chemical engineering

The problem

Chlorine is a highly toxic oxidizing agent. It dissociates to free radicals in strong UV light. Almost all metals resist attack by dry chlorine. When wet it forms hydrochloric acid, HCl, which is also very corrosive – see the note for Hydrochloric acid (10%, 36%) for details.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Carbon steel	PET	Glass
Stainless steels	HDPE	Graphite
Titanium	PTFE	
(Monel)	PVC	
(Hastelloy C)		
(Alloy 20 (40Fe, 35Ni, 20Cr, 4Cu))		

Underlying mechanisms

Free radical attack; acid attack when wet.

Fluorine, F₂

Where found

Fluorine is used to make PTFE and other fluoro-polymers, to produce uranium hexafluoride (for nuclear power), as an etchant in semi-conductor manufacture, and as an insulator in electrical systems (SF₆).

Industrial sectors

Chemical engineering

The problem

Fluorine, like chlorine, is a highly toxic oxidizing agent. It dissociates to free radicals in strong UV light. Many metals resist fluorine gas when dry (titanium, however, is attacked). When wet it forms hydrofluoric acid, HF, which is highly corrosive to metals – see note for [Hydrofluoric acid](#) for details.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Stainless steels	HDPE	Graphite
Carbon steels	PTFE	
(Monel)		
(Hastelloy C)		
(Alloy 20 (40Fe, 35Ni, 20Cr, 4Cu))		

Underlying mechanisms

Free radical attack; acid attack when wet.

Oxygen, O₂

Where found

Oxygen is the third most abundant element and makes up 21% of the atmosphere of the planet. It is extracted and used for a range of industrial processes such as metal refining, oxy-acetylene welding, the cracking of hydrocarbons, and sewage treatment. Pure oxygen is used in emergency breathing equipment and rocketry.

Industrial sectors

Chemical engineering, transport (rockets)

The problem

Materials that are stable in the earth's atmosphere will combust in pure oxygen, particularly if it is under pressure. Liquid oxygen spills, if allowed to soak into organic materials such as fabrics and asphalt can cause them to detonate unpredictably on mechanical impact. The propensity of polymers to combine with oxygen is measured by its *oxygen index*: the concentration of oxygen required to maintain steady burning (it is a measure of flammability). A high oxygen index means a high resistance to self-sustained burning. In theory, a material with an oxygen index greater than 21% will extinguish itself in air at atmospheric pressure; most burn fiercely in pure oxygen. Metals that do not form a protective oxide film can burn in oxygen – iron and steel, for example, combust in pure oxygen at or above atmospheric pressure. Metal powders are explosive in pure oxygen.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Stainless steels	PTFE	Glass
Titanium	(Other fluorocarbons)	
Aluminium		
(Hastelloy C)		
(Alloy 20 (40Fe, 35Ni, 20Cr, 4Cu))		
(Gold)		

Underlying mechanisms

Free radical attack

Sulphur dioxide (dry), SO₂

Where found

Sulphur dioxide is commonly used a preservative for dried fruit, in wine making as an antioxidant, as a refrigerant, and is used industrially in the production of sulphuric acid. If it escapes into the atmosphere it can cause acid rain.

Industrial sectors

Food processing, domestic, chemical engineering

The problem

Sulphur dioxide is a toxic reducing agent. When wet it forms sulphuric acid, H₂SO₄, which is highly corrosive to metals – see note for Sulphuric acid (10%, 70%) for details.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Stainless steels	PTFE	Glass
High carbon steels	EPDM	Graphite
Mild steels	POM	
Aluminium alloys		
(Monel)		
(Hastelloy C)		
(Alloy 20 (40Fe, 35Ni, 20Cr, 4Cu))		

Underlying mechanisms

Acid attack, free radical attack

Durability: the built environment

Science note

Durability of built environments

The materials of construction – those used for housing; industrial buildings; industrial, rural and marine structures; – must withstand exposure to the atmosphere, to sunlight and UV radiation, and to the effects of wind and rain. They are used in very large quantities, so the choice is guided not only by durability but by cost. Many of the materials of architecture – carbon steels or woods, for instance – do not resist atmospheric conditions in wet countries as well as stainless steels or glazed brick, but because they are cheaper it is economic to use and protect them with paints or preservatives than to use the materials that are intrinsically most durable.

The database characterizes the *durability* of the material exposed to a number of standard operating environments on a 4-point scale: *1: Unsuitable; 2: Usable only with protection; 3: Good, with only slight degradation, 4: Excellent.* The categorization is designed to help with screening; further information should always be sought if environmental attack is a concern. The notes linked to the environments provide some guidance.

Industrial atmospheres

Industrial atmospheres contain airborne particulates, oxides of carbon, nitrogen and sulphur, and other corrosive substances. They present a challenging environment for the durability of building components. Metals used as building enclosure cladding, flashing, railings, fascias, and soffits are particularly vulnerable. Carbonate-based stone (limestone, marble) and low-fired brick are eroded; acid run-off attacks reinforcement in concrete causing spalling of the cover, woods and metal are attacked by chemical deposits.

Rural atmospheres

Rural atmospheres are relatively benign, presenting the lowest threat to the materials of construction, which, however, are still exposed to moisture and UV radiation (see also [Water and aqueous environments](#) and [Sunlight and UV radiation](#), below).

Marine atmospheres

The presence of salt, high humidity, exposure to storms, and high winds make the marine environment a challenging one for materials. Hurricanes and high-energy storms present occasional but severe stress. Continual wetting and drying of surfaces with salt saturated water and intense solar radiation can be just as damaging over the lifetime of the structure.

Sunlight and UV radiation

Polymers and elastomers age when exposed to oxygen and light (particularly UV). This causes loss of strength, stiffness and toughness, also discoloration and loss of gloss. This is countered by additives: *antioxidants, light stabilizers* and *fluorescent whitening agents*. Some of these are so universal that the “standard” grade of the polymer already contains enough of one or another of them to give it acceptable resistance; PP, ABS, PS, PET, PMMA, PC, Nylons, and PU all need UV protection. Special grades are more heavily protected. For more information, see [Durability: UV radiation](#).

Further reading

Author	Title	Chapter
Ashby et al	Materials: Engineering, Science, Processing and Design	17
Budinski	Engineering Materials: Properties and Selection	7
Callister	Materials Science and Engineering: An Introduction	15

[Further reference details](#)

Environments

Industrial atmosphere

Where found

Electric power generation, material extraction and processing, manufacturing and transport all, to varying degrees, create emissions of carbon dioxide, oxides of nitrogen and sulphur, caustic particulates and acidic residues. These combine to create an industrial atmosphere.

Industrial sectors

Petroleum, engineering manufacture, construction, energy conversion

The problem

Industrial atmospheres represent a challenging environment for the durability of building components. The combination of airborne particulates and acidic discharges from industrial sites can be very damaging. Metals used as building enclosure such as cladding, flashing, railings, fascias, and soffits are particularly vulnerable. Polymers, brick, and even stone are attacked by industrial atmospheres.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Stainless steels	PVC	Soda-lime glass
Aluminium alloys	Polyurethane	Borosilicate glass
Lead	Epoxy	Brick
Bronze	Polyester	Concrete
Cast iron	PTFE	Granite
	Nylon	Slate
	CFRP	(Glazed ceramic)
	GFRP	
	Polyurethane	
	Polyethylene	
	Polypropylene	

Underlying mechanisms

Acid attack, oxidation

Rural atmosphere

Where found

Rural atmospheres are those free of the emissions of large-scale industry and remote from salt water or spray.

Industrial sectors

Construction, domestic

The problem

Rural atmospheres present fewer problems than industrial or marine atmospheres, but the damaging effects of UV radiation, repeated cycles of wetting and drying and the threat of bacterial and insect attack remain.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Galvanized steel	Epoxies	Soda-lime glass
Epoxy coated steel	Polyester	Borosilicate glass
Aluminium alloys	PVC	Brick
Bronze	GFRP	Granite
Copper	CFRP	Sandstone
	Wood	Limestone
	Polyurethane	Slate
	Polyethylene	(Glazed ceramic)
	Polypropylene	

Underlying mechanisms

Oxidation, bacterial or insect attack

Marine atmosphere

Where found

Marine atmospheres are encountered in off-shore and marine environments and on land within range of wind-carried salt spray.

Industrial sectors

Marine engineering, engineering manufacture

The problem

The prevalence of salts, high humidity, exposure to storms, and high winds make marine environments a challenging context for buildings. Hurricanes and high-energy storms present an obvious threat, but continual wetting and drying of surfaces with salt saturated water and intense solar radiation can be just as damaging over the lifetime of the building.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Galvanized steel	Epoxies	Soda-lime glass
Epoxy coated steel	Polyester	Borosilicate glass
Stainless steels	PTFE	Brick
Aluminium alloys	Nylon	Granite
Bronze	PVC	Sandstone
Copper	GFRP	Limestone
	CFRP	Slate
	Polyurethane	(Glazed ceramic)
	Polyethylene	
	Polypropylene	

Underlying mechanisms

Oxidation, aqueous solution, acid attack

Ultraviolet (UV) radiation

Where found

Ultraviolet (short wavelength, high energy) radiation is a component of sunlight. Much is filtered out by ozone (O₃) in the earth's atmosphere, but enough gets through to damage polymers and other organic materials. UV exposure increases with altitude, becoming particularly strong at the altitudes used for civil aviation.

Industrial sectors

Construction, aerospace

The problem

Polymers and elastomers age when exposed to light (particularly UV) and oxygen, causing loss of strength, stiffness and toughness, discoloration, and loss of gloss. This is countered by additives: *antioxidants*, *light stabilizers* and *fluorescent whitening agents*. Some of these are so universal that the "standard" grade of the polymer already contains enough of one or another of them to give it acceptable resistance; PP, ABS, PS, PET, PMMA, PC, Nylons, and PU all need UV protection.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Carbon steel	PTFE	Glass
Stainless steel	PE	Brick
Bronze	PP with UV filter	Concrete
	PVC with UV filter	
	Styrene-butadiene rubber with UV filter	

Inhibitors

Polymer additives: antioxidants, light stabilizers, and fluorescent whitening agents.

Underlying mechanisms

Polymer degradation, free radical attack

Durability: flammability

Science note

Definition and measurement

Ceramics and glasses do not burn. Metals, if dispersed as a fine powder are potentially combustible, but in bulk, flammability is not normally an issue, even for magnesium. Most polymers, on the other hand, are inherently flammable, although to differing degrees. Here we rank flammability on a four point scale: *Non-flammable, Self-extinguishing, Slow burning and highly flammable*.

There are several ways to characterize flammability of polymers. The most logical is the *Limiting oxygen index (LOI)*: it is the oxygen concentration in % required to maintain steady burning. Fresh air has about 21% oxygen in it. A polymer with an oxygen index lower than this will burn freely in air; one with an oxygen index that is larger will extinguish itself unless a flame is played onto it – then it burns. Thus a high oxygen index means resistance to self-sustained burning. Less logical, but much used, is the *Underwriters Laboratory (UL94) rating* in which a strip of polymer 1.6 mm thick is held horizontally (H) or vertically (V) and ignited. Its response is recorded as a code such as HB, meaning "horizontal burn". The scales are compared in Table 1.

Oxygen index (LOI)	UL 94 (1.6mm) rating	Flammability
Up to 16	Unrated	Highly flammable
16-20	HB	
21-24	HB	Slow burning
25-29	V-2	
30-43	V-0	Self extinguishing
Over 44	V-0 or better (e.g. 5V)	

Table 1. Flammability ratings compared.

All woods are flammable, but the rate of burning depends on moisture and resin content. Wood species are graded by the flame-spread index, a measure of the distance spread on a flat wood surface under standard conditions and the ISO 9705 room/corner test, which simulates full scale conditions of a house fire. Flame-retarding treatments reduce the rate of wood burning by a factor of up to 2, but do not prevent it. Because of these complexities, woods and wood-derived products are all rated as "Highly flammable" in the database.

Many building materials incorporate inorganic components such as plaster with combustibles like polymers, woods and paper. An approximate measure of the degree of combustibility is given by the percentage of organic ingredients.

Drilling down: how do polymers burn and how do you stop them?

Combustion is an exothermic reaction in which hydrocarbons are oxidized to CO₂ and H₂O. Sounds simple, but it isn't. Combustion is a gas phase reaction; the polymer or its decomposition products must become gaseous for a fire to begin. When you light a candle you are melting the wax and raising it to the temperature at which it pyrolyzes (400 – 800°C) to gaseous hydrocarbon decomposition products. These gasses react in the flame – the bit you can see – to produce heat, which melts and pyrolyzes more wax.

A fully developed fire results when an ignition source like a spark or cigarette ignites combustible material such as paper. Its heat radiates out causing other combustible materials (particularly polymers and fabrics) to decompose into a flammable gas mix. Flashover

(Figure 1) occurs when these gasses ignite, instantly spreading the fire over the entire area and producing temperatures of over 1000°C.

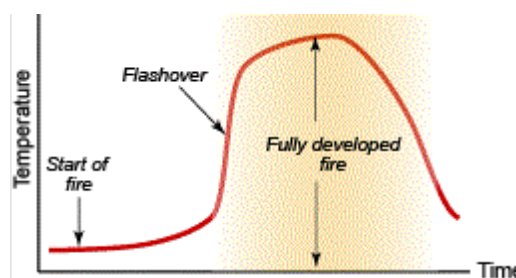


Figure 1. The temperature rise during a fire.

Combustion is a free-radical reaction. At high temperatures hydrogen, together with one electron from its covalent bond (symbol **H•**) is freed from a carbon atom of the polymer molecule, leaving a highly reactive free

radical **R•** in the gas. The hydrogen radical reacts with oxygen and the hydrocarbon radical to give CO₂ and heat, releasing the **H•** again to propagate the reaction further.

Flame retardants work in one of two ways. Some scavenge the free radicals, tying them up harmlessly and so retarding or snuffing out the combustion reaction. These are usually compounds containing chlorine or bromine; they, too, pyrolyze to give free radicals **Cl•** and **Br•** that attach themselves to the hydrocarbon radical, removing it from the reaction. Others work by creating a protective layer of water vapour between the solid polymer and the gaseous decomposition products, limiting heat transfer, cooling it, and reducing pyrolyzation. Typical among these are additions of Mg(OH)₂; that decompose at about 300°C, releasing H₂O and leaving inert MgO.

Polymer breakdown in sunlight, too, is linked to free radicals – see [Durability: UV radiation](#).

Further reading

Author	Title	Chapter
Ashby et al	Materials: Engineering, Science, Processing and Design	17
Budinski	Engineering Materials: Properties and Selection	7
Callister	Materials Science and Engineering: An Introduction	15

[Further reference details](#)

Property

Flammability

Where found

High temperature or flame in the presence of oxygen creates the risk of burning. Many materials are flammable: exposed to a flame they combust, though some will self extinguish when the flame is removed. The propensity to combust – the flammability – is measured on a 4-point scale: highly flammable, slow-burning, self-extinguishing, and non-flammable.

Industrial sectors

Petroleum, engineering manufacture, construction, energy conversion, domestic

The problem

Most polymers are flammable in ambient conditions if exposed to flames. Many, when burning, emit toxic smoke. Even those that are self-extinguishing are damaged by heat and flame.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Carbon steel	PTFE	Glass
Stainless steel	Phenolics	Brick
Cast iron	Neoprene	Concrete
Aluminium	Epoxies with flame retardant	
Copper	GFRP with flame retardant	

Inhibitors

Flame retardants: halocarbons, hydroxymethyl phosphonium salts, aluminium hydroxide, magnesium hydroxide.

Underlying mechanisms

Oxidation; sulphurisation; nitridation; free radical attack

Durability: UV radiation

Science note

Definition and measurement

Polymers and elastomers, including natural polymers such as wood, age when exposed to oxygen and light (particularly UV). The degradation causes loss of strength, stiffness and toughness, and discoloration and loss of gloss (many organic solvents do the same – see Durability: organic solvents). This is countered by additives: *antioxidants*, *light stabilizers*, and *fluorescent whitening agents*. Some of these are so universal that the “standard” grade of the polymer already contains enough of one or another of them to give it acceptable resistance; PP, ABS, PS, PET, PMMA, PC, Nylons, and PU all need UV protection. Special grades are more heavily protected. The UV component of sunlight also degrades wood through the creation of free radicals which then degrade the wood polymers. Wood can be protected from degradation by spraying, dipping, or pressure treatment with UV absorbing translucent preservatives. The ranking given here is on a 4-point scale: *Poor, Fair, Good or Excellent*.

Drilling down: inhibiting photo-degradation

Most commercial polymers are made by processes involving chain polymerization, polyaddition, or polycondensation reactions. When exposed to radiation, chemical reactions are triggered that change their chemical composition and molecular weight. These reactions, called *photo-oxidation* or *photo-degradation*, lead to a change in the physical and optical properties of the polymer. Once this starts, it sets off a chain reaction that accelerates degradation unless stabilizers are used to interrupt the oxidation cycle. Heat, too, can trigger degradation in an oxygen-containing atmosphere.

Ultraviolet absorbers such as benzophenone or the benzotriazole function by preferentially absorbing UV radiation, follow the grandly named Beer-Lambert law, which states the obvious: that the amount of UV radiation absorbed is a function of both sample thickness and stabilizer concentration. In practice, high concentrations of absorbers and sufficient thickness of the polymer are required before enough absorption takes place to effectively retard photo-degradation. *Hindered amine stabilizers* (HALS) are a more efficient way to stabilize against light-induced degradation of most polymers. They do not absorb UV radiation, but act to inhibit degradation of the polymer; their efficiency and longevity are due to a cyclic process wherein the HALS are regenerated rather than consumed during the stabilization process. HALS stabilizers can be effective in concentrations of 0.01–0.05%; absorbers, such as benzophenones, are effective in concentrations of ~0.5%. A third UV protection strategy is the use of ‘blockers’ or ‘light screens’, notably carbon black, TiO₂ pigment, or nano-scale clay particles, effective at contents of 2% wt or more.

Further reading

Author	Title	Chapter
Ashby et al	Materials: Engineering, Science, Processing and Design	17
Callister	Materials Science and Engineering: An Introduction	17

[Further reference details](#)

Durability: thermal environments

Science note

Aspects of thermal environments

The maximum and minimum service temperatures give some idea of the temperature range over which a material can safely be used, but it is a crude one. Material suitability for use in a given thermal environment depends on its resistance to chemical breakdown, on its resistance to corrosion or attack by the atmosphere, on its function (carrying load, providing thermal insulation etc.), and on its planned life-time. The best choice of material is that which best copes with all of these.

Check-list of applications and materials

Figure 1 identifies some of the materials and applications associated with given ranges of temperature. The notes linked to each of the ranges in the database give more information.

T °C	Materials	Applications	T °K
1200	Refractory metals: Mo, W, Ta Alloys of Nb, Mo, W, Ta Ceramics: Oxides Al ₂ O ₃ , MgO, etc. Nitrides, Si ₃ N ₄ , Carbides, SiC	Rocket nozzles Special furnaces Experimental turbines	1400
1000	Austenitic stainless steels Nichromes, nimonics Nickel based super-alloys Cobalt based super-alloys Iron based superalloys	Gas turbines Chemical engineering Petrochemical reactors Furnace components Nuclear construction	1200
800	Iron-based super-alloys Ferritic stainless steels Austenitic stainless steels Inconels and nimonics	Steam turbines Superheaters Heat exchangers	1000
600	Low alloy steels Titanium alloys (up to 450°C) Inconels and nimonics	Heat exchangers Steam turbines Gas turbine compressors	800
400	Fiber-reinforced polymers Copper alloys (up to 400°C) Nickel, monels and nickel-silvers PEEK, PEK, PI, PPD, PTFE and PES (up to 250°C)	Food processing Automotive (engine)	600
200	Most polymers (max temp: 80 to 150°C) Magnesium alloys (up to 150°C) Aluminum alloys (up to 150°C) Monels and steels	Civil construction Household appliances Automotive Aerospace	400
0	Austenitic stainless steels Aluminum alloys	Rocket casings, pipework, etc. Liquid O ₂ or N ₂ equipment	200
-200	Copper alloys Niobium alloys	Superconduction	0
-273			

Figure 1. Materials to resist thermal environments for each regime of temperature.

Further reading

Author	Title	Chapter
Ashby et al	Materials: Engineering, Science, Processing and Design	12, 13, 17
Ashby & Jones	Engineering Materials Vol 1 & 2	Vol. 1, Chap. 20, 22, 24, 25
Askeland	The Science and Engineering of Materials	23
Budinski	Engineering Materials: Properties and Selection	13, 21

[Further reference details](#)

Environments

Tolerance of cryogenic temperatures (down to -273°C)

Where found

Aircraft, oilrigs and other structures in polar regions must tolerate temperatures as low as -60°C . Industrial refrigeration operates down to -70°C . Liquefied natural gas involves temperatures as low as -160°C . The most extreme temperatures are encountered in deep space, in superconducting magnets and sensors, and in the storage and use of fuels such as liquid oxygen and hydrogen. The most usual cryogenic media are liquid nitrogen (boiling point -196°C) and liquid helium (boiling point -269°C).

Industrial sectors

Engineering manufacture; construction, medical engineering

The problem

Corrosion rates at cryogenic temperatures are low. The main problem is that of brittleness: almost all polymers and many metals lose their toughness, making them vulnerable to brittle fracture. The exceptions, among metals, are those with a face-centred cubic structure.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Austenitic stainless steels	PTFE, (PCTFE) to -273°C	Most ceramics are suitable for low temperature use
Aluminium alloys	HDPE to -270°C	
Copper alloys	PET to -160°C	
Nickel alloys	(Polyimides to -250°C)	
Lead alloys	Most polymers: to -30°C	

Underlying mechanisms

Embrittlement

Tolerance of temperatures up to 150°C

Where found

Most structures are required to operate between 0 and 100°C.

Industrial sectors

All industrial sectors

The problem

Materials with very low melting points (such as lead and tin) and polymers with low heat-deflection temperatures begin to deform by creep at temperatures approaching 100°C

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
All metals except lead and tin, which creep rapidly at 150°C.	ABS	All ceramics and glasses
	PC	
	CA	
	PA	
	PEEK	
	PMMA	
	PVC	
	Epoxy	
	Polyester	
	CFRP	
	GFRP	
	SMC	
	BMC	

Tolerance of temperatures up to 250°C

Where found

Temperatures in this range are found in food processing (including household ovens), in chemical manufacture, and cooler part of internal combustion engines.

Industrial sectors

Engineering manufacture; food processing; chemical engineering; construction; domestic; petroleum engineering

The problem

Polymers (excluding PTFE and PEEK) and low melting point metals deform rapidly by creep as temperatures approach 250°C.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Carbon steels	PTFE to 250°C	Soda glass
Stainless steels	PEEK to 250°C	Borosilicate glass
Copper alloys	PA (nylon) to 200°C	All ceramics
Aluminium alloys	GFRP to 220°C	
Nickel alloys	CFRP to 220°C	
	BMC to 220°C	
	SMC to 220°C	

Underlying mechanisms

Oxidation, polymer breakdown

Tolerance of temperatures up to 450°C

Where found

Heat exchangers, oil refinery and chemical processing plants, steam turbines and gas turbine compressors require materials able to withstand at least 450°C.

Industrial sectors

Engineering manufacture, chemical engineering, energy conversion, construction, petroleum engineering

The problem

All polymers are unstable in this temperature range. Many metals start to oxidize or react with combustion gasses (particularly those containing sulphur) causing loss of section. Ceramics tolerate the temperature but because of their brittleness they are seldom used in load-bearing components.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Low alloy steels	None	Borosilicate glass (Pyrex)
Stainless steels		Refractory brick
Titanium alloys		Concrete
Nickel based superalloys (Nimonic)		Most ceramics

Underlying mechanisms

Oxidation, sulphur attack

Tolerance of temperatures up to 850°C

Where found

Superheaters, heat-treatment furnaces, heat exchangers in gas turbines, advanced steam turbines, and much chemical engineering equipment operate in this temperature range.

Industrial sectors

Engineering manufacture, chemical engineering, energy conversion, construction, petroleum engineering

The problem

All polymers are unstable in this temperature range. Most metals creep, oxidize or react with combustion gasses (particularly those containing sulphur), causing loss of section. Ceramics tolerate the temperature but because of their brittleness they are seldom used in load-bearing components.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Stainless steels	None	Refractory brick
Iron-based superalloys		Most ceramics
Nickel-based superalloys		(Pyroceram)
Nichrome		
(Nimonic)		
(Cobalt based superalloys)		

Underlying mechanisms

Oxidation, sulphur attack

Tolerance of temperatures above 850°C

Where found

Gas turbines, chemical manufacture, petrochemical reactors, high temperature furnaces for processing and heat treatment, nuclear reactor cores, and rocket nozzles and combustion chambers

Industrial sectors

Engineering manufacture, chemical engineering, energy conversion, construction, petroleum engineering

The problem

Few metals can withstand temperatures above 850°C. Those that can are based on the complex alloys of the high-melting metals Fe, Ni, W, Co, Ta, Mo, and Nb.

Preferred materials and coatings

Metals	Polymers and composites	Ceramics and glasses
Stainless steels	None	Alumina, Al ₂ O ₃
Iron-based superalloys		Silicon carbide, SiC
Nickel-based superalloys		Silicon nitride, Si ₃ N ₄
Nichromes		Zirconia, ZrO ₂
Tungsten		
(Cobalt based superalloys)		
(Molybdenum alloys)		
(Tantalum alloys)		
(Niobium alloys)		
(Platinum)		

Underlying mechanisms

Oxidation, sulphur attack

Further reading references



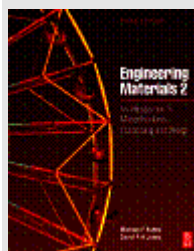
Ashby, M. F. (2009) *Materials and the Environment: Eco-informed Material Choice*, Butterworth-Heinemann, Oxford, UK. ISBN 978-1-85617-608-8



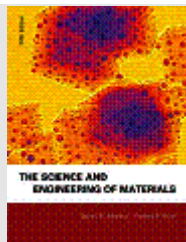
Ashby, M. Shercliff, H. and Cebon, D. (2007) *Materials: Engineering, Science, Processing and Design*, Butterworth-Heinemann, Oxford, UK. ISBN 0-7506-8391-0



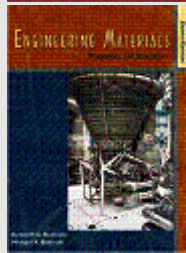
Ashby, M. F. and Jones, D. R. H. (2005) *Engineering Materials 1: An Introduction to Properties, Applications and Design*, 3rd edition, Elsevier Butterworth-Heinemann, Oxford, UK. ISBN 0-7506-6380-4



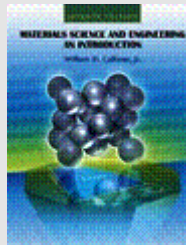
Ashby, M. F. and Jones, D. R. H. (2006) *Engineering Materials 2: An Introduction to Microstructures, Processing and Design*, 3rd edition, Elsevier Butterworth-Heinemann, Oxford, UK. ISBN 0-7506-6381-2



Askeland, D. R. and Phulé, P. P. (2006) *The Science and Engineering of Materials*, 5th edition, Thomson, Toronto, Canada. ISBN 0-534-55396-6



Budinski, K. G. and Budinski, M. K. (2004) *Engineering Materials: Properties and Selection*, 8th edition, Prentice Hall, Upper Saddle River, New Jersey, USA. ISBN 0-1318-3779-6



Callister, W. D. (2007) *Materials Science and Engineering: An Introduction*, 7th edition, John Wiley & Sons, New York, USA. ISBN 0-471-73696-1



Shackelford, J. F. (2009) *Introduction to Materials Science for Engineers*, 7th edition, Pearson Prentice Hall, Upper Saddle River, NJ, USA. ISBN 0-13-601260-4