

**Aluminium Bronze Alloys
Corrosion Resistance Guide**

Publication No 80, 1981

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Copper Development Association

Copper Development Association is a non-trading organisation sponsored by the copper producers and fabricators to encourage the use of copper and copper alloys and to promote their correct and efficient application. Its services, which include the provision of technical advice and information, are available to those interested in the utilisation of copper in all its aspects. The Association also provides a link between research and user industries and maintains close contact with other copper development associations throughout the world.

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Introduction

This publication - one of a series issued by the Copper Development Association Aluminium Bronze Advisory Service dealing with different aspects of the use of copper-aluminium alloys - generally known as aluminium bronzes - is intended to provide design engineers with facts and figures on which they can base their choice of materials.

Section 1 provides a brief survey of the corrosion resistance of aluminium bronzes and the reasons for using these alloys in various corrosive situations. More detailed information on all aspects of the corrosion behaviour of aluminium bronzes follows in Sections 2, 3 and 4.

Section 2 discusses the compositions and metallurgical structures of the different aluminium bronze alloys in most common use and relates these features of the alloys to their corrosion performance. In Section 3 the different types of corrosion experienced in engineering service are described and an indication is given of the relative resistance of different aluminium bronzes and of some of their principal competitive materials.

Section 4 discusses the use of aluminium bronzes in a variety of industries and environments - indicating again the relative suitability of different alloys and materials for the purposes concerned.

Quantitative data supporting the statements concerning corrosion resistance of aluminium bronzes is included where appropriate. Wherever possible the particular aluminium bronze alloy to which the data refer is stated but for some of the older information, alloy compositions may not be identical with those now used. *It must also be borne in mind that the important effects of metallurgical structure on corrosion resistance of aluminium bronzes were not well understood at the time that some of the older data were generated and the results quoted are, therefore, often for material which does not have the most favourable structure. Consequently the corrosion rates quoted are sometimes significantly higher than would be expected from material of corresponding composition produced nowadays.*

1 General Survey

The aluminium bronzes are a family of copper-base alloys containing approximately 5% to 11% aluminium, some having additions of iron, nickel, manganese or silicon. They include alloys suitable for sand casting, gravity diecasting and for the production of forgings, plate, sheet, tube, strip, wire and extruded rods and sections. Compared with other copper alloys, the higher strength of the aluminium bronzes is combined with excellent corrosion resistance under a wide range of service conditions. Maximum corrosion resistance is provided by control of the composition and manufacturing history of the material as discussed in detail in Section 2(i).

Aluminium bronzes are the most tarnish-resistant copper alloys and show no serious deterioration in appearance and no significant loss of mechanical properties on exposure to most atmospheric conditions. Their resistance to atmospheric corrosion combined with high strength is exploited, for example, in their use for bearing bushes in aircraft frames. Aluminium bronzes also show low rates of oxidation at high temperatures and excellent resistance to sulphuric acid, sulphur dioxide and other combustion products and are, therefore, used for the construction of items exposed to either or both these conditions. For example, aluminium bronzes are used very successfully for inert gas fans in oil tankers. These operate under highly stressed conditions in a variable but very corrosive atmosphere containing salt-laden water vapour, sulphurous gases and carbon.

No engineering alloy is immune to corrosion. Corrosion resistance depends upon the formation of a thin protective film or layer of corrosion products which prevents or substantially slows down the rate of attack. The aluminium content of aluminium bronzes imparts the ability to form, very rapidly, an alumina-rich protective film which is highly protective and is not susceptible to localised breakdown and consequent pitting in the presence of chlorides. Aluminium bronzes are, therefore, very resistant to corrosion by sea water and probably find more use in sea water service than in any other environment.

Virtually all metals and alloys in common use are susceptible to some extent to crevice corrosion, i.e. accelerated attack within or just at the edge of areas shielded by close proximity to other components or by deposits on the surface. Crevice corrosion in service is particularly objectionable when it takes the form of pitting or severe surface roughening on shafts or valve spindles in the way of bearings or seals.

Any crevice corrosion of aluminium bronzes, however, takes the form of minor selective phase dealloying as described in Section 3(iii), Section 3(iv) and Section 3(v) which results in little reduction of strength and practically no impairment of surface finish. Aluminium bronzes are, therefore, very widely used for pump shafts and for valve spindles - situations where pitting corrosion in crevices makes stainless steels, for example, unsuitable.

A form of selective phase dealloying of aluminium bronzes commonly known as 'dealuminification' which caused some concern some years ago is no longer a significant problem. This type of attack, similar to the dezincification of duplex bronzes, results in selective dissolution of the principal alloying element (in this case aluminium) from one phase of the alloy leaving a residue of porous copper which retains the original shape and dimensions of the component but has little strength. By controlling the composition and, for the alloys of high aluminium content, the cooling rate from casting or working temperature, metallurgical structures are ensured that will not suffer dealuminification to any significant extent under any normal conditions of use.

Metal failures in service are often the result of the combined influence of corrosion and mechanical factors, the most common being stress corrosion, which occurs under the simultaneous action of high tensile stress and an appropriate corrosive environment, and corrosion fatigue which occurs under cyclic stressing in a corrosive environment. Brasses, for example, show high susceptibility to stress corrosion in the presence of even small quantities of ammonia, and austenitic stainless steels suffer stress corrosion cracking in hot chloride solutions. High resistance to stress corrosion cracking is an important reason for the use of aluminium bronzes by the British Navy for underwater fastenings. High tensile bronzes, formerly used for this service, were very liable to fail by stress corrosion but stress corrosion failures of aluminium bronze fasteners have proved extremely rare.

High resistance to corrosion fatigue is essential for marine propellers and it is principally for that reason that most large propellers are made from nickel aluminium bronze. This material is quite outstanding in resistance to corrosion fatigue in sea water, being much superior to high tensile brass or to stainless steels. Manganese aluminium bronze, which is also used for large propellers, also has high corrosion fatigue strength though somewhat inferior to nickel aluminium bronze.

Turbulent water flow conditions can cause local erosion of the protective films on which alloys depend for their corrosion resistance and result in localised deep attack by a combination of corrosive and erosive action. The corrosion/erosion resistance of the aluminium bronzes is substantially higher than that of the bronzes and similar to that of 70/30 copper-nickel which is generally recognised to be one of the alloys most resistant to this type of attack.

At higher water flow rates, such as exist in pumps and on some areas of marine propellers, formation and collapse of vapour cavities in the water can produce very high local stresses leading to cavitation damage. The resistance of alloys to cavitation damage generally increases with their resistance to corrosion fatigue and with their ability to reform protective films rapidly on the metal freshly exposed by cavitation erosion. The advantages of aluminium bronze over most other alloys in these respects have already been mentioned and it will be no surprise, therefore, that aluminium bronzes show exceptionally high resistance to cavitation damage. This is an important feature in their use for marine propellers and the principal reason for their use for impellers in high duty pumps.

However, the soundness of the casting has a very significant bearing on resistance to cavitation erosion and impingement attack, and maximum resistance cannot be expected from a casting produced by bad foundry practice.

One further property of aluminium bronzes should be mentioned in this general survey of their corrosion resistance. In most practical engineering situations different metals or alloys are used in contact with each other in the presence of an electrolyte such as sea water or fresh water. In these circumstances the possibility of galvanic action, causing accelerated attack on the less noble metal, can be very important. Aluminium bronzes are slightly more noble than most other copper alloys and slightly less noble than the copper-nickel alloys but the differences are too small to cause significant galvanic effects. Monel, stainless steel and titanium are all considerably more noble than aluminium bronze but it is found in practice that, providing the exposed area of the more noble metal does not greatly exceed that of the aluminium bronze, very little acceleration of corrosion of the aluminium

bronze occurs. It is for this reason that aluminium bronze tubeplates are used in condensers with titanium tubes.

2 Types of Aluminium Bronze

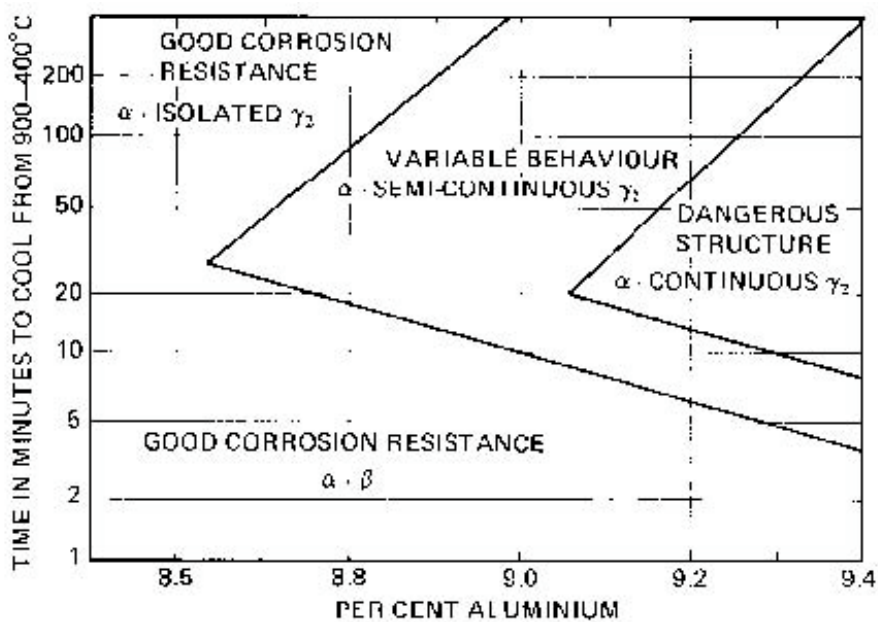
The copper-aluminium alloys commonly known in English-speaking countries as "aluminium bronzes" contain approximately 5% to 11% aluminium, some having additions of iron, nickel, manganese or silicon.

All the aluminium bronzes have good corrosion resistance but they vary in this respect according to their metallurgical structure which in turn depends upon the composition of the material and its manufacturing history - especially the thermal treatment to which they have been subjected.

i Metallurgical Structure

The simple aluminium bronzes containing only copper and aluminium have a single phase (alpha) structure up to about 8% aluminium. Above that level a second phase (beta) is formed producing an alpha-beta alloy. Whereas in brasses the formation of beta phase results in a substantial reduction in corrosion resistance this is not true of the beta phase in the copper-aluminium system. Consequently, while alpha-beta brasses have a much lower corrosion resistance than alpha brasses, alpha-beta aluminium bronzes have a resistance to general corrosion which is similar to that of alpha aluminium bronzes and a superior resistance to corrosion/erosion and to cavitation corrosion.

Figure 1 – Influence of aluminium content and cooling rate on the corrosion resistance of binary copper aluminium alloys.



Taken from B Upton, *Corrosion*, 1963, 19 (6), 204t.

This is true of aluminium bronzes containing only alpha and beta phases but if an alpha-beta aluminium bronze is allowed to cool too slowly from temperatures above about 600°C the beta phase converts to a mixture of alpha and gamma 2 phases at around 565°C. The gamma 2 phase has a higher aluminium content than the beta phase and shows a susceptibility to corrosion rather similar to that of the beta phase in brasses. Consequently if gamma 2 is formed as a continuous network a higher rate of penetration of corrosion through the alloy can occur and the corrosion resistance is seriously affected. Small isolated areas of gamma 2 phase will result in localised superficial corrosion but this will not penetrate into the body of the material. Research carried out in M.O.D. (Navy) laboratories established the influence of aluminium content and of cooling rate for alloys containing 8.5 to 9.5% aluminium and demonstrated that the formation of a continuous network of gamma 2 can be avoided by keeping the aluminium content below 9.1%. The corrosion behaviour of alloys containing between

8.7 and 9.1% aluminium is variable depending upon the cooling rate but even at the slowest cooling rates likely to be found in commercial practice the gamma 2 phase in this range of composition is discontinuous. Freedom from gamma 2 phase can be ensured in material of higher aluminium content by rapid cooling, for example, by water quenching, from 600°C after casting or hot working. Alternatively material containing gamma 2 as a result of too slow a cooling rate after casting, hot working or welding may be reheated to 600 to 800°C for sufficiently long to reform the beta phase and then quenched. The effect of aluminium content and cooling rate on the structure and corrosion resistance of binary aluminium bronzes is shown in Figure 1.

The comments above concerning the formation of gamma 2 phase with resultant deterioration of corrosion resistance apply only to binary aluminium bronzes, i.e. alloys of copper and aluminium without additional alloying elements. The presence of iron in sufficient quantity suppresses the formation of gamma 2 and also refines the grain structure of the alloy; consequently any gamma 2 that is present is more likely to be in a discontinuous form. About 2% iron is generally sufficient to do this in sections with a diameter up to about 75 mm, but this is not sufficient for heavier sections. Nickel has a similar effect to iron in suppressing the formation of gamma 2 in a dangerous form but is not used for that purpose since iron is almost equally effective and cheaper. Manganese additions will also suppress the breakdown of beta phase to alpha plus gamma 2 but, at the same time, modifies the character of the beta making it more susceptible to corrosion. A manganese content must, therefore, be chosen which gives the optimum balance between these two effects. Thus BS 1400 AB1 restricts the manganese content to a maximum of 1.0% and it is usual to maintain it below 0.75%.

The higher strength aluminium bronze alloys such as AB2 (castings) and CA104 (wrought) contain nominally 10% aluminium with 5% each of iron and nickel. In these alloys the beta phase breaks down during cooling through the temperature range 950 to 750°C to produce alpha plus kappa. The alloy solidifies with an all-beta structure from which the kappa phase begins to precipitate as coarse particles (often in the form of rosettes) at about 900°C. At lower temperatures the remaining beta is transformed into alpha plus kappa, the kappa commonly being of a lamellar form. Subsequent slow cooling to room temperature results in further precipitation of fine kappa within the alpha grains. The kappa phase is of variable composition containing aluminium, iron, nickel and manganese (if manganese is present) and its formation effectively increases the amount of aluminium which can be present in the alloy before the danger of gamma 2 formation arises. Gamma 2 is consequently not normally present in nickel aluminium bronzes and these alloys show very high resistance to corrosion. To ensure that the kappa phase itself is corrosion resistant the nickel content of the alloy should exceed the iron content and the manganese content should not exceed 1.3%.

Aluminium silicon bronze containing approximately 2% silicon with 6% aluminium and 0.5% iron is not at present covered by any British Standard specification but the wrought forms will be included in the next revision of BS 2872 and 2874. It is widely used in the form of forgings, extruded rods and sections and as castings under Ministry of Defence Ship Department Standards DG Ships 1044 and 129. The aluminium content of this alloy is sufficiently low for there to be no danger of gamma 2 phase formation under any normal conditions of manufacture or use.

The copper manganese aluminium alloys CMA1 and 2 are normally classified as aluminium bronzes, although they contain about 12% manganese in addition to approximately 8.5% aluminium. These alloys have an alpha-beta structure but the beta phase is of a quite different composition from that in the binary aluminium bronzes and has lower resistance to corrosion under some conditions, as discussed in Section 3(iv).

3 Types of Corrosion

Metals can be affected by corrosion in many different ways ranging from uniform dissolution to highly localised pitting or cracking. The undesirable results of corrosion may range from leakage, fracture of the component concerned, or contamination of the product being handled by the equipment. The principal forms of corrosion experienced in practice are outlined in the following sections with an indication of the comparative resistance of aluminium bronzes and their principal competing materials to the different forms of attack.

i Uniform or General Corrosion

The amount of metal removed by general corrosion in sea water or fresh water is insufficient to cause significant damage to components in any of the non-ferrous metals or alloys in normal commercial use. In some aggressive waters, pure copper and some of the high copper alloys such as bronzes and gunmetals can, however, introduce sufficient copper into the water to cause increased corrosion of galvanized steel or of aluminium alloys downstream of the copper alloy components. Aluminium bronzes are virtually unaffected by cupro - solvent waters and no problems from copper pick-up are experienced in connection with aluminium bronze components.

Acidic solutions cause relatively rapid dissolution of many copper alloys but aluminium bronzes are very little affected by non-oxidizing acids and are widely used for handling sulphuric acid, for example.

ii Pitting

Pitting corrosion is important because of its localised character which can result in perforation of the wall of a valve, pump casting, water tube or other vessel in a relatively short time. All common metals and alloys are subject to pitting corrosion to a greater or less extent under certain conditions of service. Stainless steels form deep pits of very small cross section in waters of high chloride content.

Pitting in copper alloys is not directly associated with chloride content and they do not normally show significant pitting, for example, in sea water service. Sulphide pollution of the sea water may cause pitting in most copper alloys including aluminium bronzes; for polluted waters copper alloys containing tin are usually best.

iii Crevice Corrosion

Practically all metals and alloys suffer accelerated local corrosion either within or just outside crevices or "shielded areas" where two components or parts of the same component are in close contact with one another but a thin film of water can penetrate between them. The effect is greatest for stainless steels which depend upon free access of oxygen to the wetted surfaces to maintain the protective oxide film on which their corrosion resistance depends. Crevice corrosion of stainless steels usually takes the form of severe pitting within the crevice and this is a serious limitation on the uses to which these alloys may be put. Crevice corrosion of copper-nickel alloys takes a different form, resulting in a narrow trench of corrosion at the edge of the crevice often with some deposition of copper on the metal surface within the crevice. Most other copper alloys show similar crevice corrosion but to a greater or lesser extent. Crevice corrosion of aluminium bronzes tends to occur within the crevice and usually takes the form of selective phase attack and dealloying as discussed in Section 3(iv) and Section 3(v).

The effects are, therefore, related to the metallurgical structure of the particular aluminium bronze concerned and are least in the single phase alloys. None of the aluminium bronzes, however, is seriously affected by crevice corrosion in the way that stainless steels may be, since the attack does not produce pitting or serious roughening of the surface.

iv Selective Phase Attack

In duplex and multiphase alloys the phases have different electrochemical potentials and there is consequently always a tendency for the most anodic phase to be corroded preferentially. The extent to which this occurs depends upon how great the potential difference is between the anodic phase and the surrounding phases and upon the distribution and intrinsic corrosion resistance of the anodic phase. The most commonly encountered examples of selective phase corrosion are in the duplex brasses such as free machining brass, diecasting and hot stamping brasses, Muntz metal, naval brass and the high tensile brasses commonly called manganese bronzes. The beta phase in all these alloys is anodic to the alpha and forms a continuous network providing a continuous path of low corrosion resistance by which attack can penetrate deeply into the alloy.

The danger of selective phase attack occurring on the gamma 2 phase in aluminium bronzes has already been discussed in Section 1 where it was also explained that the formation of this phase can be avoided by suitable control of composition and/or cooling rate. Under free exposure conditions in fresh waters or sea water, aluminium bronzes free from gamma 2 phase do not show selective phase corrosion but, under crevice conditions, beneath deposits or marine growths or under the influence of galvanic corrosion or of electrical leakage corrosion, selective phase attack can occur. In the alpha-beta alloys this takes the form of slightly preferential attack on the beta phase. In the nickel aluminium bronzes selective phase attack may affect small amounts of residual beta phase if any is present but is more likely to affect the narrow band of alpha phase immediately adjoining the lamellar kappa and to spread from that into the kappa phase itself. This selective phase attack in aluminium bronzes is not usually of great significance and occurs only when they are subjected to particular severe service conditions. For such conditions of service it can be beneficial to apply to nickel aluminium bronze castings the heat treatment required in DGS Specification 348 (six hours at 675°C + 15°C followed by cooling in still air). This is, however, only necessary if the rate of cooling of the casting from about 900°C has been too rapid for formation of the normal alpha-plus-kappa structure.

The copper manganese aluminium alloys CMA1 and 2 are essentially of alpha-beta structure but the beta phase is of different composition from that in the aluminium bronzes of low manganese content and is more susceptible to selective phase corrosion. This does not occur, however, to any significant extent under free exposure and rapidly flowing water conditions such as exist on marine propellers. In static sea water service - especially under shielded area conditions or under the influence of galvanic coupling to more noble alloys - severe selective phase corrosion of the beta phase can occur and, since the beta phase is continuous, can cause serious deterioration.

v Dealloying

A form of corrosion affecting some copper alloys results in selective removal of the principal alloying element leaving a residue of copper. This residue has a porous structure and very low strength but it retains the shape and approximate dimensions of the original alloy. Consequently the depth to which the attack has penetrated is very difficult to assess except by destructive methods such as the preparation of metallographic sections. The most common example of dealloying is provided by the duplex brasses in which the selective phase attack on the beta phase takes the form of dezincification with effective removal of zinc and formation of a weak copper residue.

A similar type of corrosion known as dealuminification occurs when selective phase attack takes place in aluminium bronzes. The conditions under which it occurs are those under which selective phase corrosion is experienced, as described in Section 3(iv). It can be very largely prevented under most conditions of service by ensuring that the alloy used is free from gamma 2 phase.

Selective phase corrosion in the CMA alloys takes the form of dealloying of the beta phase. The conditions under which it occurs have already been discussed in Section 3(iv). The susceptibility of CMA alloys to selective phase dealloying corrosion is less than that of the duplex brasses but much greater than that of the aluminium bronzes with low manganese content which should always be used in preference to CMA for applications involving static or shielded area conditions in sea water and for acidic environments.

vi Corrosion/Erosion

All common metals and alloys depend for their corrosion resistance on the formation of a superficial layer or film of oxide or other corrosion product which protects the metal beneath from further attack. Under conditions of service involving exposure to liquids flowing at high speed or with a high degree of local turbulence in the stream, this protective film may be prevented from forming or may be eroded away locally exposing unprotected bare metal. The continued effect of erosion, preventing permanent formation of a protective film, and the corrosion of the bare metal consequently exposed can lead to rapid local attack causing substantial metal loss and often penetration. This type of attack is known as corrosion/erosion or impingement attack. (See Table 1, Table 2 and Table 7.)

The highest resistance to corrosion/erosion is shown by alloys on which the protective film reforms very rapidly if it should suffer mechanical damage and on which the film itself is resistant to erosion. Stainless steels are particularly resistant to this type of attack. Unalloyed copper is relatively poor but all copper alloys are substantially more resistant than copper itself and nickel aluminium bronze is among the most resistant of all the copper alloys.

Table 1 – Corrosion/Erosion Attack in Jet Impingement Tests at 9.3 m/s

Temperature	Material	Attack at Jet	
		Diameter mm	Depth mm
15°C	Cast nickel aluminium bronze	10	0.12
	Wrought 70/30 copper-nickel	14	0.10
10°C	Cast nickel aluminium bronze	0	0
	Wrought 70/30 copper-nickel	2.1	0.05

Jet impingement tests on cast nickel aluminium bronze DGS 348 and 70/30 copper-nickel condenser tube CN107 have been carried out at 10°C and 15°C by BNF Metals Technology Centre using natural sea water at a water jet velocity of 9.3m/s. The extent of corrosion/ erosion occurring at the jets in 28-day tests is given in Table 1. The diameter or depth of attack recorded is the average for four specimens.

vii Cavitation Damage

Under water flow conditions even more severe than those responsible for corrosion/erosion, cavitation damage may occur. This is the result of formation of small vapour bubbles (cavitation) in the water in regions where the flow conditions produce low pressures and subsequent violent collapse of these bubbles on the surface of the metal in neighbouring areas where the local pressure is higher. The stresses generated by the collapse of cavitation bubbles are much greater than those associated with corrosion/erosion and are often sufficient not only to remove protective corrosion product films but actually to tear out small fragments of metal from the surface - usually by fatigue. The metal freshly exposed as a result of this action will of course be subject to corrosion and the resultant damage is due to a combination of corrosion and the mechanical forces associated with the bubble collapse. In view of the magnitude of the mechanical forces associated with cavitation damage the contribution made by corrosion is, however, relatively small.

Cavitation damage is a serious problem principally in high duty pump impellers and marine propellers but can occur sometimes in restricted waterways of valves working at high flow rates. It can be reduced by correct hydrodynamic design of the propeller or pump but it is not usually possible to produce a design which will ensure freedom from cavitation under the full range of operating conditions that have to be covered. Nickel aluminium bronze shows exceptionally high resistance to cavitation damage and is for that reason the alloy most commonly used for production of large marine propellers and high duty pump impellers. (See Table 3a and Table 3b.)

Table 2 – Resistance of Copper Alloys to Impingement Attack and General Corrosion in Sea Water

Alloy	Composition % (Bal.Cu)					28-dayJet Impingement 20°C	14-day Brownsdon & Bannister 20°C	Water in Slow Motion	Water Speed 10 m/s
	Al	Fe	Ni	Mn	Zn				
Aluminium Bronze	8.2	1.7	-	-	-	0.04	0.19	0.15	0.17
Nickel Aluminium Bronze	8.2	2.9	4.3	2.4	-	0.00	0.32	0.04	0.10
Nickel Aluminium Bronze	8.8	3.8	4.5	1.3	-	0.00	0.28	0.04	0.16
Manganese Aluminium Bronze	7.6	2.8	3.1	10.0	-	0.01	0.24	0.04	0.11
High Tensile Brass	0.8	0.8	0.2	0.5	37.0	0.03	0.08	0.09	0.73
	Sn	Zn	Pb						
Gunmetal	9.7	1.4	0.6			0.02	0.32	0.14	0.74
Gunmetal						0.23	0.39	0.22	1.66

The data in Table 2 is taken from a paper, "The Resistance of Copper Alloys to Different Types of Corrosion in Sea Water", by Sigmund Bog of the Ship Research Institute of Norway, presented at the 7th Scandinavian Corrosion Congress, Trondheim, 1975.

Table 3a – Cavitation Erosion in 3%NaCl Solution

Published data for resistance to cavitation erosion generally refer to tests carried out using equipment in which the specimen is vibrated at 20 kHz. Such tests in 3% sodium chloride solution at an amplitude of ± 0.025 mm reported by A Tuffrey in "Vibratory Cavitation Erosion Testing", National Engineering Laboratory Report No. 149, April 1964, produced the following depths of attack:	
Material	Depth of Attack
Nickel aluminium bronze AB2	< 0.025 mm in 7 hours
Austenitic stainless steel 321	0.305 mm in 7 hours
High tensile brass HTB1	0.280 mm in 6 hours

Table 3b – Cavitation Erosion Rates in Fresh Water

I. S. Pearshall (Chartered Mechanical Engineer, July 1974) gives the following cavitation erosion rates from tests at 20 kHz in fresh water:	
Material	Cavitation Erosion Rate
	Mm³/hour
Nickel aluminium bronze A32	0.6
Aluminium bronze AB1	0.8
Manganese aluminium bronze CMA1	1.5
High tensile brass HTB1	4.7
Gunmetal G1	4.9
Monel K500 (cold drawn)	2.8
Monel K500 (aged)	1.2
Austenitic stainless steel 321	1.7
Austenitic stainless steel 316	1.7
Cast martensitic stainless steel 420	1.7
Cast austenitic stainless steel 347	1.0
Spheroidal graphite cast iron	1.3
Ni-resist cast iron	4.4

viii Stress Corrosion

Stress corrosion is a highly localised attack occurring under the simultaneous action of tensile stress and an appropriate environment. The total amount of corrosion is very small but cracking occurs in a direction perpendicular to that of the applied stress and may cause rapid failure. The environments conducive to stress corrosion cracking vary for different types of alloy. Stainless steels suffer stress corrosion cracking particularly in hot chloride solutions. Most copper alloys show susceptibility to stress corrosion cracking in the presence of ammonia or ammonium compounds and in some moist sulphur dioxide environments. They vary, however, in their degree of susceptibility, the brasses being the most susceptible and copper-nickel alloys the least susceptible. Aluminium bronzes are much superior to brasses, though not as good as copper-nickel in this respect. (See Table 4 and Table 5.)

The possibility of stress corrosion cracking can be reduced to a minimum by ensuring that components are given a stress relief heat treatment to remove internal stresses arising from working or welding and by keeping assembly stresses in fabricated equipment as low as possible by accurate cutting and fitting of the component parts. Service stresses are, however, frequently unavoidable and where these are likely to be high the low susceptibility of the aluminium bronzes, and especially of the nickel aluminium bronzes, to stress corrosion is an important consideration.

Stress corrosion cracking may follow a transgranular or intergranular path depending upon the alloy and the environment. In the presence of ammonia, stress corrosion cracking of aluminium bronzes follows a transgranular path. Intergranular stress corrosion cracking can occur, however, in the single phase alloys such as CA106 ("Alloy D ") in high pressure steam service. Research in USA showed that susceptibility to this type of attack can be eliminated by the addition of 0.25% tin to the alloy. This is not provided for in British Standards at present but the American UNS Designation 61300 covers "Alloy D" with the appropriate tin addition.

It has been very recently observed that, at high tensile stress, CA106 ("Alloy D") can undergo intergranular stress corrosion cracking in hot brine also. Laboratory tests indicate that the UNS 61300 alloy resists stress corrosion under these conditions. It is, therefore, suggested that the alloy containing tin should be used not only for super-heated steam but probably also for hot brine if the operating or fabrication stresses are high. Since, however, the resistance of alloy 61300 to stress corrosion in hot brine has so far been demonstrated only in laboratory tests it is recommended that its performance under service conditions should be checked before deciding finally upon its use.

The results in Table 5 were obtained using very severe test conditions, i.e., a high ammonia content in the atmosphere and very high stress levels (including plastic deformation) in the samples. Under normal service conditions aluminium bronzes very rarely show stress corrosion cracking.

Table 4 – Atmospheric Stress Corrosion Tests on Copper Alloys

Alloy	Temper % Cold Rolled	Time to Failure	
		New Haven	Brooklyn
70/30 brass	5C	35 - 47 days	0 - 23 days
Leaded alpha - beta brass	5L	51 - 136 days	70 - 104 days
Admiralty brass	4C	51 - 95 days	41 - 70 days
Aluminium brass	4C	221 - 495 days	311 - 362 days
Aluminium bronze (9.7% Al, 3.86% Fe)	4C	> 8.5 years	> 8.5 years

The results in Table 4 were obtained from atmospheric exposure tests of U-bend specimens exposed to industrial environments (J. M Popplewell and T. C. Gearing, Corrosion, 1975, 31, 279).

Table 5 - Comparison of Stress Corrosion Resistance of Brasses, Aluminium Bronzes and Copper-Nickel Alloys

Alloy	Time to 50% Relaxation (hours)
Arsenical admiralty brass	1.30
Muntz metal	1.35
Naval brass	1.50
70/30 brass	1.51
Aluminium brass	1.80
5% aluminium bronze	4.08
8% aluminium bronze	5.94
10% copper-nickel	234
PDO copper	312
30% copper-nickel	= 2000

Stress corrosion tests were carried out by D. H. Thompson (Mater Res. & Std., 1961,1, 108) using loop specimens of sheet material exposed to moist ammoniacal atmosphere. The ends of the loops were unfastened once every 24 hours and the extent of relaxation from the original configuration was measured. This is a measure of the progress of stress corrosion cracking on the outside surface of the loop. Table 5 gives the time to 50% relaxation for various alloys tested.

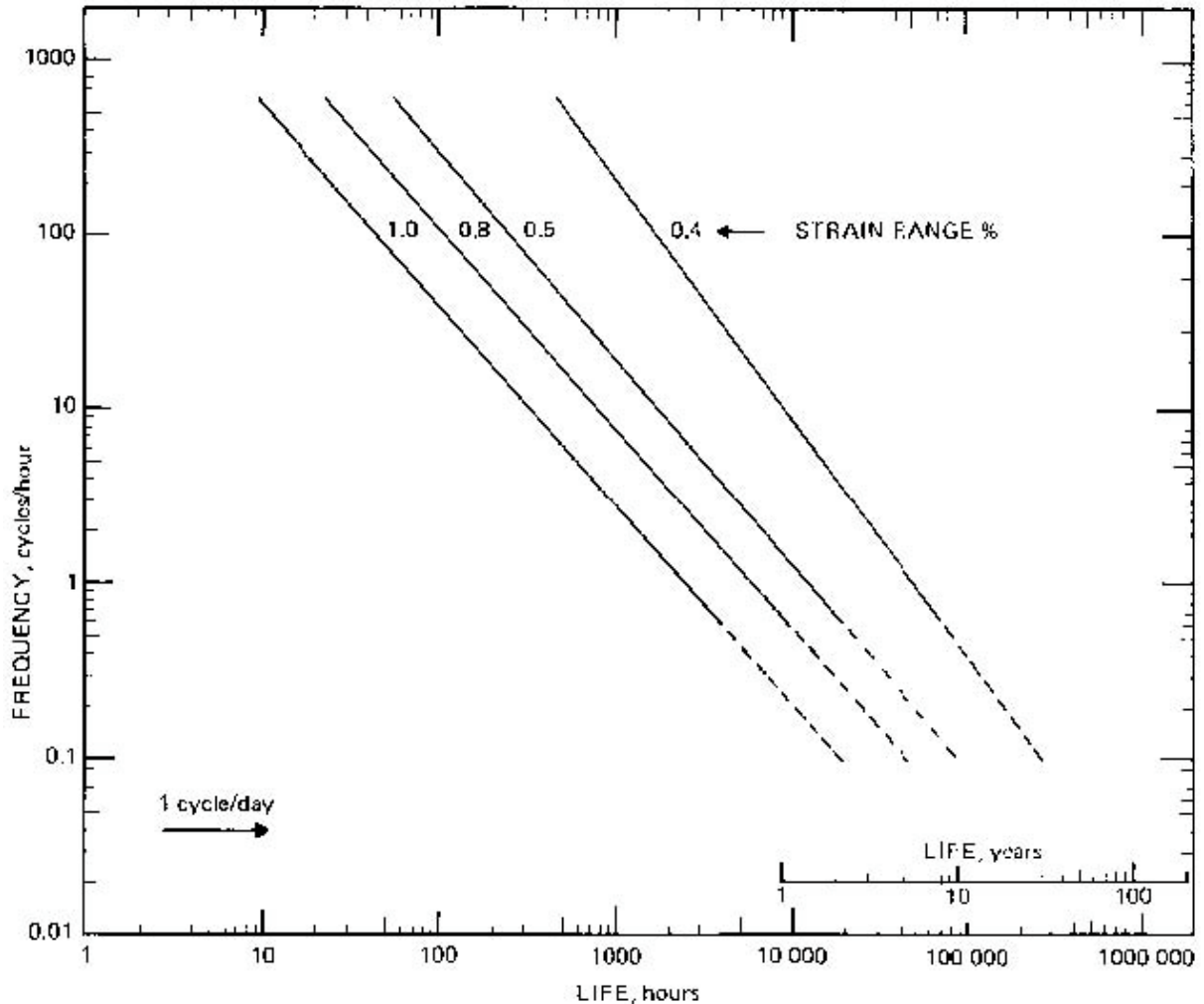
The results in Table 5 were obtained using very severe test conditions, i.e. a high ammonia content in the atmosphere and very high stress levels (including plastic deformation) in the samples. Under normal service conditions aluminium bronzes very rarely show stress corrosion cracking.

ix Corrosion Fatigue

Metals and alloys can fail by fatigue as a result of the repeated imposition of cyclic stresses well below those that would cause failure under constant load. In many corrosive environments the cyclic stress level to produce failure is further reduced, the failure mechanism then being termed corrosion fatigue. The relative contributions to the failure made by the corrosion factor and the fatigue factor depend upon the level of the cyclic stress and upon its frequency, as well as upon the nature of the corrosive environment. Under high frequency loading conditions such as may arise from vibration or rapid pressure pulsing due to the operation of pumps, etc., the corrosion resistance of the alloy is of less importance than its mechanical strength but under slow cycle high strain conditions both these properties become important. Because of their combination of high strength with high resistance to normal corrosive environments, aluminium bronzes, and particularly the nickel aluminium bronzes (which are the best in both these respects), show excellent corrosion fatigue properties under both high frequency and low frequency loading conditions.

Figure 2 - High strain/low cycle corrosion fatigue results for cast nickel aluminium bronze DGS 348.

Taken from Ship Department Publication 18 "Design and Manufacture of Nickel Aluminium Bronze Sand Castings", Ministry of Defence (PE), 1979, Figure 2 presents results of corrosion fatigue tests carried out in sea water at 32°C. The tests employed flat specimens strained by bending about a zero strain mean position.



x Galvanic Corrosion

When two metals or alloys are used in contact with one another in an electrolyte such as water they affect one another's resistance to corrosion. Usually one of the pair - the more "noble" - will cause some degree of accelerated corrosion of the other and will itself receive a corresponding degree of protection. A useful guide to interactions at bimetallic contacts is provided by the British Standards Institution "Commentary on Corrosion at Bimetallic Contacts and Its Alleviation" PD 6484: 1979. This groups together all varieties of aluminium bronze and the silicon bronzes and the information that it gives is, therefore, of somewhat limited value but differences between aluminium bronzes with respect to galvanic corrosion are usually negligible.

Galvanic corrosion tests are usually carried out in sea water since this and fresh water are the environments in which mixtures of metals are most frequently encountered. Such tests show most aluminium bronzes to be slightly more noble than other copper alloys with the exception of 70/30 copper-nickel. The differences are, however, small and the additional corrosion of aluminium bronzes produced by coupling to copper-nickel or of other copper alloys by coupling to aluminium bronze is usually insignificant.

Stainless steels and titanium are both more noble than aluminium bronzes but the degree of acceleration of attack produced by coupling to these materials is normally only slight. Tubeplates of aluminium bronze are commonly used for heat exchangers with titanium tubes and experience has confirmed that galvanic attack on the tubeplate is negligible.

The absence of significant galvanic effects under these conditions depends partly upon the effective exposed area of the titanium tube ends being not greatly in excess of that of the aluminium bronze. In situations where aluminium bronze is used in contact with and in close proximity to much larger areas of more noble materials such as titanium, stainless steel or nickel-copper alloys of the Monel type appreciable accelerated attack may sometimes be experienced. This usually takes the form of selective phase attack and dealloying as described in Section 3(iv) and Section 3(v).

xi Electrical Leakage Corrosion

Situations are sometimes met in service where aluminium bronze components are inadvertently exposed to electrical leakage currents either as a result of electrical faults resulting in current passing to earth, via a submerged pump for example, or as a result of incorrect positioning of impressed current cathodic protection equipment resulting in current passing from the water on to the metal equipment at one point and leaving it again at another. These conditions will accelerate attack of practically all metallic materials whether the current concerned is DC or AC. Aluminium bronze under these conditions will show local corrosion in the region affected by the current leakage, the corrosion usually taking the form of selective phase dealloying. The avoidance of this type of attack is obviously a matter of correct design and maintenance of the electrical equipment concerned.

xii Corrosion Associated with Welds

Welding can adversely affect the corrosion resistance of many alloys and in different ways. Galvanic corrosion can result from differences in composition or of structure between the filler and the parent metal. The metallurgical structure of the heat-affected zone adjoining the weld may be changed for the worse especially in multipass welding in which the time at elevated temperature is relatively long. Welding under conditions of restraint can also introduce stresses in the weld metal and in the heat-affected zones of the parent metal which may lead to stress corrosion cracking.

The most widely recognized harmful effect of welding on corrosion resistance is observed in stainless steels which are not either of very low carbon content or stabilised by the addition of titanium or niobium. Diffusion of chromium and formation of chromium carbides in the heat-affected zone leaves chromium-depleted material which is readily corroded, resulting in a line of attack close to the weld - commonly known as "weld decay". A reduction of corrosion resistance in the heat-affected zones of welds may occur, to a smaller extent and for different reasons, in some of the aluminium bronzes.

The aluminium bronzes most commonly used under conditions where welding is required are the single phase alloy CA106 ("Alloy D"), and the nickel aluminium bronze alloys CA105 and AB2. The welding of aluminium bronzes is dealt with in the CDA Aluminium Bronze Advisory Service publication, "Guidance Notes for Welding Aluminium Bronze Alloys", and only those aspects directly concerned with corrosion resistance will be discussed here.

Since problems of weld cracking can arise in welding CA106 with a matching filler unless the impurity levels in both the filler and parent metal are closely controlled it is common practice to use a duplex alloy filler containing ~ 10% Al. To avoid selective phase corrosion of the beta phase in the filler on subsequent service in sea water or in acid solutions, it is recommended that an overlay with a composition matching the parent metal should be applied on top of the duplex filler. If a matching filler rod is not available an overlay of nickel aluminium bronze is used.

The possibility of tensile stresses and consequent increased susceptibility to stress corrosion cracking arising as a result of welding under conditions of restraint has already been noted. A further factor to be watched in welding CA106 is the formation of microfissures in the heat-affected

zone during welding which can act as stress raisers and so further increase the danger of stress corrosion cracking in subsequent service.

No serious corrosion problems are introduced in welding CA105. The use of an approximately matching filler ensures that galvanic effects between the filler and parent metal are reduced to a minimum although the aluminium content of the weld bead will usually be higher than that of the parent metal. The good high-temperature ductility of CA105 also means that there is little likelihood of microfissuring occurring and the level of stress in the heat-affected zone arising from welding under restraint is also likely to be less than in CA106 welded under similar conditions.

Nickel aluminium bronze castings may be welded to repair small areas of casting porosity, etc., or in the manufacture of large components or water circulating systems. The welding is usually carried out using a filler with approximately the same composition as the parent metal but welds made under conditions of severe restraint require a duplex filler to avoid weld cracking. A nickel aluminium bronze overlay must then be applied to avoid corrosion of the filler. In sea water service, selective phase dealloying corrosion of the alpha phase immediately adjacent to lamellar kappa sometimes occurs in the outer regions of the heat affected zones of welds in nickel aluminium bronze. The attack is sometimes accelerated by the presence of internal stresses in the casting which produce cracking in the porous copper produced by the dealloying corrosion and accelerate the rate of penetration of attack into the alloy.

Welding of nickel aluminium bronze castings can also reduce the corrosion resistance of the material by the presence of beta phase retained in the weld bead as a result of its cooling rapidly from the temperature at which conversion to alpha-plus-kappa begins. Beta phase may also be reformed from the alpha-plus-kappa in the heat-affected zone of parent metal nearest the weld.

Welded nickel aluminium bronze which has had no post-weld heat treatment is widely used in seawater and other environments without difficulty. Under severe service conditions, however, the beta phase formed by either of these mechanisms can suffer selective phase dealloying.

This possibility can be eliminated by the application of a post-weld heat treatment. The treatment laid down in the requirements of DG Ships Specification 348 is six hours at $675^{\circ}\text{C} \pm 15^{\circ}\text{C}$ followed by cooling in still air. This ensures conversion of retained beta to alpha-plus-kappa and also modifies the lamellar kappa and greatly reduces the possibility of selective phase attack on the adjacent alpha.

4 Varieties of Service

The combination offered by aluminium bronzes of high strength, high corrosion resistance and availability in a number of different forms results in their being used under a wide variety of conditions and by a wide variety of industries. Their principal fields of use are sea water service, water supply, the chemical and petrochemical industries and certain high temperature and corrosive atmosphere applications.

i Sea Water Service

Aluminium bronzes are used in marine engineering for deck and underwater fittings ranging from fasteners to propellers. Pumps, valves and heat exchangers in ships and in land-based installations using sea water for cooling all employ aluminium bronzes.

Marine Propellers

The requirements for materials for marine propellers are high resistance to corrosion fatigue, corrosion/erosion and cavitation erosion, a high strength-to-weight ratio, good castability and tolerance of welding and local working for repairing damage sustained in service. The choice of alloys for the manufacture of large propellers essentially reduces to nickel aluminium bronze, manganese aluminium bronze and high tensile brass ("manganese bronze").

Results of corrosion fatigue tests on cast material always show a considerable scatter and the values obtained depend upon such factors as the size of specimen and the frequency of loading. Most

published results, however, agree in showing the corrosion fatigue strength of nickel aluminium bronze in sea water to be approximately twice that of high tensile brass, with manganese aluminium bronze falling about midway between these two (See Table 6). Among the ferrous alloys spheroidal-graphite cast iron has a corrosion fatigue strength approximately equal to that of high tensile brass. The incorporation of nickel and chromium in the austenitic grade produces no improvement in corrosion fatigue strength although the general corrosion resistance of the material is considerably improved. Cast austenitic stainless steel is also reported to have a fatigue strength approximately equal to that of high tensile brass.

Note, however, that since results of corrosion fatigue tests are dependent on factors such as test bar design and size, and test frequency, comparisons between results from different sources should only be made with caution.

Nickel aluminium bronze shows higher corrosion/erosion resistance than high tensile brass - in which this form of attack tends to be selective upon the beta phase - and its resistance to cavitation erosion is greater than that of high tensile brass by a factor of about eight. Manganese aluminium bronze offers corrosion/erosion resistance approximately equal to that of nickel aluminium bronze with somewhat inferior resistance to cavitation erosion.

Repair welding of high tensile brass propellers can introduce a corrosion hazard since this alloy is susceptible to stress corrosion cracking in sea water and is, therefore, liable to suffer stress corrosion in the weld and heat-affected zone, where residual stresses remain, unless a stress relief heat treatment is carried out after welding. Manganese aluminium bronze also shows susceptibility to stress corrosion cracking, although to a considerably smaller extent, and must also be given a stress relief heat treatment after welding. Nickel aluminium bronze requires more care in welding to avoid formation of cracks in either the weld or the parent metal but, since it is not subject to stress corrosion in sea water, no subsequent stress relieving treatment is required.

The blades, hub body, hub cone and bolts of variable pitch propellers can be made from nickel aluminium bronze or from stainless steel. Stainless steels have higher resistance to corrosion/erosion but are considerably more susceptible to cavitation damage and are more prone to damaging crevice corrosion. Consequently nickel aluminium bronze is usually the preferred material.

Table 6 - Corrosion Fatigue Properties of Marine Propeller Alloys

Material	Time (days)	Seawater or 3% NaCl	Corrosion Fatigue Strength (10^8 cycles) N/mm ²	Source
NiAlbronze - AB2	50	Seawater	± 87	(a)
MnAlbronze - CMA1	50	Seawater	± 62	(a)
HTbrass - HTB1	50	Seawater	± 42	(a)
NiAlbronze - AB2-Type (2,3)	23	3% NaCl	± 108	(b)
MnAlbronze - CMA1 (2)	23	3% NaCl	± 91	(b)
HTbrass - HTB1 (2)	23	3% NaCl	± 62	(b)
NiAlbronze - AB2-Type (3)	35	3% NaCl	± 122	(b)
MnAlbronze - CMA1	35	3% NaCl	± 89	(b)
HTbrass - HTB1	35	3% NaCl	± 74	(b)
Spheroidal graphite cast iron (ferritic)	23	3% NaCl	± 46	(c)
Spheroidal graphite cast iron (austenitic)	23	3% NaCl	± 46	(c)
13% Cr. stainless steel	23	3% NaCl	± 54	(d)
19/11 austenitic stainless steel	50	Seawater	± 45	(e)

(1) (a) Todd, B., Trans. I. Mar. E., 1968, 80

(b) Webb, A W O, Eames, C F W and Tuffrey, A, Symposium 'Propellers 75', Soc Naval Architects and Marine Engineers, USA 1975.

(c) British Cast Iron Research Association

(d) Stone Manganese Marine Limited

(e) Bulletin Sea Horse Institute, May 1963.

(2) Samples cut from propellers. All other results for cast test pieces.

(3) Nickel aluminium bronze from this source is the proprietary alloy "Nikalium".

Tables of corrosion fatigue results from various sources are presented in Chapter 8, "Propellers", by A. W. O. Webb and H. Capper in "Materials for Marine Machinery", Ed. S. H. Frederick and H. Capper, The Institute of Marine Engineers/Marine Media Management Limited, London, 1976. Data taken from these are combined in Table 6.

Other Underwater Fittings

Nickel aluminium bronze, manganese bronze and high tensile brass are all used for cast underwater fittings such as propeller shaft brackets and rudders and in conditions of free exposure to sea water are satisfactory. For fittings to be used under conditions where deposits of silt or mud may form on them, high tensile brass and manganese aluminium bronze are both liable to show dealloying of the beta phase. The nickel aluminium bronze may show slight attack of this type in the alpha phase adjoining the lamellar kappa but to a very much smaller extent. High tensile brass and manganese aluminium bronze are not suitable for underwater fasteners because of their liability to stress corrosion cracking. Nickel aluminium bronze CA104 or DGS 1043, aluminium silicon bronze DGS 1044, phosphor bronze or Monel are used. Phosphor bronze and Monel are, however, of lower strength than nickel aluminium bronze.

Sea Water Pumps

Nickel aluminium bronze is widely used for impellers in centrifugal pumps due to its excellent resistance to both corrosion/erosion and cavitation damage. For the most severe applications or where long life and reliability are particularly important the pump body can also be made of nickel aluminium bronze together with the shaft and the fasteners but the body is often made of gunmetal. Gunmetal impellers may be used in pumps operating under relatively low speed conditions. Monel

impellers may be used in high duty pumps but these do not normally offer any advantage over nickel aluminium bronze and are usually more expensive. Cast austenitic stainless steel impellers may be cheaper than nickel aluminium bronze but do not provide the same strength or resistance to cavitation damage. These materials are also less reliable for shafts because of their liability to pitting corrosion in the gland area during shut-down periods.

Some sea water pumps have cast iron bodies with impellers of gunmetal, nickel aluminium bronze, Monel or austenitic stainless steel. During the early life of such pumps the cast iron provides some sacrificial protection to bronze or Monel impellers but the corrosion of the cast iron takes the form of selective phase corrosion leaving a surface that is essentially graphite. A heavily graphitized pump body is strongly cathodic to non-ferrous impeller materials and can cause accelerated attack on them. Consequently the use of aluminium bronze or other non-ferrous impellers is not recommended for sea water pumps with cast iron bodies if long service is expected. Cast austenitic steel impellers are preferable in those circumstances.

Valves

Valves in salt water systems with steel or galvanized steel pipework are usually also of ferrous material but are protected internally by non-metallic coatings. The discs and seats are usually of cast nickel aluminium bronze or Monel and the stems of wrought nickel aluminium bronze or phosphor bronze but sometimes of Monel or 70/30 copper-nickel. High tensile brass is not suitable for the valve stems because of its liability to dezincification nor are stainless steels because of their liability to pitting in crevices.

For systems using copper alloy pipework, gunmetal valves are most commonly used - frequently with nickel aluminium bronze stems - but for high integrity systems valves made entirely from aluminium bronze or from copper-nickel are used. Nickel aluminium bronze has the advantage of greater strength and is usually less expensive than copper-nickel for this purpose.

Heat Exchangers

Steam condensers, oil coolers and other heat exchangers operating on sea water usually have tubes of aluminium brass or of copper-nickel. Aluminium bronze CA102 is manufactured in tube form but is not very often used in heat exchangers. There is an increasing tendency to use titanium tubes for condensers and heat exchangers where conditions are very severe or where extended trouble-free life is essential - for example, drain coolers in ships and main condensers in electricity generating stations.

The "traditional" material for heat exchanger tubeplates is rolled naval brass and this is usually satisfactory with tubes of aluminium brass or 90/10 copper-nickel. Experience of deep dezincification in naval brass tubeplates used with 70/30 copper-nickel tubes in main condensers led the British Navy, several years ago, to change to aluminium bronze CA106 for tubeplates. As a result of subsequent experience of occasional local dealloying corrosion of CA106 a further change was made to CA105 which has proved quite satisfactory. CA106 is, however, very widely used with copper-nickel tubes in sea water cooled condensers and heat exchangers without problems.

Apart from titanium-clad steel, aluminium bronze CA105 or CA106 is the only satisfactory material for tubeplates in heat exchangers using titanium tubes. CA105 is preferred since its reliability from the corrosion point of view is higher, but it is harder and somewhat more difficult to drill. Waterboxes and covers for heat exchangers and condensers are usually of rubber-coated cast iron or steel but, in desalination plant, waterboxes fabricated by welding 90/10 copper-nickel are often used. CA106 (UNS Alloy 61400) or the corresponding alloy with addition of tin (UNS Alloy 61300) are suitable provided that appropriate care is taken over welding (Section 3(xii) and Section 3(viii)).

Pipework

Sea water piping is often of steel or galvanized steel if first cost is a ruling factor and corrosion failures will not result in serious loss or damage. For higher quality systems 90/10 copper-nickel is used, 70/30 copper-nickel being occasionally employed where maximum strength and corrosion

resistance are required. These properties can be obtained also from aluminium bronze and there is consequently interest in the use of pipes made from aluminium bronze by welding. Such pipework should show resistance to corrosion and corrosion/erosion equal to or better than 90/10 copper-nickel but with a better strength/weight ratio.

ii Water Supply

The principal use of aluminium bronzes in the water supply industry is for pumps of the centrifugal and axial flow types but it is also employed for valve trim - especially for valve spindles.

Pumps

For pumps handling fresh waters the corrosive conditions are obviously less severe than in sea water systems but impeller tip velocities are nevertheless usually too high for gunmetals, and aluminium bronzes are, therefore, specified. AB1 is sometimes used but the higher resistance of AB2 to corrosion/erosion makes it a better choice - even for pumps where the expected flow conditions are such that AB1 might be considered adequate. Very long working lives are expected from pumps in the water supply industry and the service conditions often change, usually making greater demands on the pumps.

Centrifugal pump bodies are sometimes of cast iron but more frequently of gunmetal or aluminium bronze to avoid contamination of the water by corrosion of the cast iron. The shrouds of axial flow pumps can be made of cast iron since they can be effectively protected by non-metallic coatings. Pump spindles are usually of nickel aluminium bronze or stainless steel. Stainless steel rarely suffers pitting attack in this type of pump since the pumps are normally operated continuously.

Valves

The larger size valves used in the water supply industry are of coated cast iron or steel but with internal trim in non-ferrous material or stainless steel. Monel and aluminium bronze AB1 or AB2 are often used, with aluminium bronze CA103 or CA104 for spindles; either will give satisfactory corrosion resistance but CA104 has higher strength. High tensile brass is sometimes used for valve spindles and is permitted by the relevant British Standards but aluminium bronze is much to be preferred because of the liability of high tensile brass to selective phase dealloying (dezincification) in some waters.

Aluminium bronze is not generally used in small stopvalves for domestic water installations except for valves that are to be installed underground. BS 5433 requires these to be made from materials immune to dezincification and permits forged aluminium bronze CA104 for all parts of the valve except the body, which is cast gunmetal.

Table 7 - Resistance to General Corrosion, Crevice Corrosion and Impingement Attack in Seawater

Alloys	General Corrosion Rate mm/year	Crevice Corrosion mm/year	Corrosion/Erosion Resistance ft/s
Wrought Alloys:			
Phosphorus deoxidised copper C106 or Admiralty brass CZ111	0.04	<0.025	6
Aluminium brass CZ110	0.05	<0.05	10
Naval brass CZ112	0.05	0.05	13
HT brass CZ115	0.05	0.15	10
90/10 copper-nickel	0.18	0.75	10
70/30 copper-nickel	0.04	<0.04	12
5% aluminium bronze CA101	0.025	<0.025	15
8% aluminium bronze CA102	0.06	<0.06	14
9% aluminium bronze CA103	0.05	<0.05	14
Nickel aluminium bronze CA104	0.06	0.075	15
Aluminium silicon bronze DGS1044	0.075	see note (1)	
17% Cr stainless steel 430	0.06	<0.075	see note (1)
Austenitic stainless steel 304	<0.025	5.0	>30
Austenitic stainless steel 316	<0.025	0.25	>30
Monel	0.025	0.13	>30
Cast Alloys:			
Gunmetal LG2	0.025	0.5	>30
Gunmetal G1	0.04	<0.04	12
High tensile brass HTB1	0.025	<0.025	20
Aluminium bronze AB1	0.18	0.25	8
Nickel aluminium bronze AB2	0.06	<0.06	15
Manganese aluminium bronzes	0.06	see note (1)	
Austenitic cast iron (AUS 202)	0.04	3.8	14
Austenitic stainless steel 304	0.075	0	>20
Austenitic stainless steel 316	<0.025	0.25	>30
3% or 4% Si Monel	<0.025	0.125	>30
	0.025	0.5	>30

The data in Table 7 is taken from Defence Standard 01/2 "Guide to Engineering Alloys Used in Naval Service: Data Sheets". The figures for general corrosion rate and crevice corrosion were determined using samples fully immersed beneath rafts in Langstone Harbour for one year. General corrosion results were provided by freely exposed specimens; crevice corrosion results by specimens held in Perspex jigs providing crevice conditions between the metal sample and the Perspex. The corrosion/erosion resistance tests were carried out using the Brownsdon and Bannister test, the specimens were fully immersed in natural sea water and supported at 60°C to a submerged jet, 0.4 mm diameter placed 1 - 2 mm away, through which air was forced at high velocity. From the minimum air jet velocity required to produce corrosion/erosion in a fourteen-day test, the minimum sea water velocity required to produce corrosion/erosion under service conditions was estimated on the basis of known service behaviour of some of the materials.

Note (1) The Defence Standard Data Sheets from which the figures in Table 7 are taken give "up to 0.5 mm/year" as the crevice corrosion rate and 14 ft/sec as the corrosion/erosion resistance limit for nickel aluminium bronze AB2 or CA104 and 8 ft/sec for aluminium silicon bronze DGS 1044. Ship Department Publication 18 "Design and Manufacture of Nickel-Aluminium-Bronze Sand Castings", Ministry of Defence (PE), 1979, gives the following corrosion data:

Self-corrosion rate: For general long-term use over several years a reasonable design value is 0.05 mm/year but under ideal conditions for nickel aluminium bronze in sea water a black film slowly forms which reduces the corrosion rate in accordance with an equation of the form: Corrosion rate ~ (time)^{-0.2}

Crevice corrosion: After the initiation period which can be about 3 - 15 months with negligible corrosion the crevice corrosion propagates at about 1 mm/year.

Impingement resistance: 4.3 m/s is an appropriate design value in clean flowing sea water."

Crevice corrosion in nickel aluminium bronze takes the form of selective phase dealloying as described in Section 3 (iii), Section 3 (iv) and Section 3 (v) and is usually of little practical significance since it has only a minimal effect on the surface finish. Crevice corrosion of austenitic stainless steels 304 and 316 - although shallower - takes the form of pitting with consequent serious deterioration of surface finish.

The Defence Standard Data Sheets suggest slightly higher corrosion/erosion resistance for aluminium bronze AB1 and CA103 than for nickel aluminium bronze AB2 and CA104 and much lower resistance for aluminium silicon bronze. Practical experience indicates, however, that the nickel aluminium bronzes are superior and aluminium silicon bronze only marginally inferior to other aluminium bronzes in this respect. It is perhaps significant that the Defence Standard Data Sheet figures for corrosion/erosion resistance were derived from Brownsdon and Bannister test results. Table 2 compares other Brownsdon and Bannister test results with those of jet impingement tests which are considered to be more representative of service behaviour.

iii Oil and Petrochemical Industries

The use of aluminium bronzes in the oil and petrochemical industries is largely restricted to pumps, heat exchangers and valves in cooling water systems, to which the comments under Section 4(i) and Section 4(ii) generally apply.

Aluminium bronze (CA102 or UNS 60800) tubes are sometimes used with tubeplates of CA105 or CA106 in heat exchangers especially when these are operating under relatively high pressure and it is desired to weld the tubes to the tubeplates. For most purposes, however, heat exchangers are tubed with aluminium brass or, for particularly severe service conditions, with titanium and the tubeplates are of naval brass or aluminium bronze CA105 or CA106.

For coolers dealing with high pressure product streams, tube-and-shell condensers are used with sea water on the shell side and the product passing through the tubes. The shells and baffles are fabricated from CA106 ("Alloy D") plate 12 to 15 mm thick, using a duplex (9 to 10% Al) alloy as the weld filler but with a capping run of CA106. The tubeplates are also of CA106; with tubes of 70/30 copper-nickel or titanium.

Aluminium bronze bolts are usually employed on submersible cooling water pumps. Monel is more commonly used for bolting flanges on large diameter undersea oil or gas pipes but there is no reason why aluminium bronzes should not be used for this purpose. Since the pipes themselves are of steel and are cathodically protected, an alternative procedure which is often used is to fit steel bolts and flanges with a "bolt protector" filled with grease fitted round the bolt shanks, and to rely upon the cathodic protection to take care of the exposed ends.

Sea water piping ranging from approximately 50 to 350 mm diameter is used on offshore oil platforms to convey cooling water and water for injection back into the well. The first generation of North Sea platforms used cement-lined steel for these but 90/10 copper-nickel is now frequently employed since it gives better corrosion resistance and a considerable reduction in weight. Welded aluminium bronze tubes would give at least equally good corrosion resistance and greater weight savings since the strength/weight ratio of aluminium bronzes is higher than that of 90/10 copper-nickel.

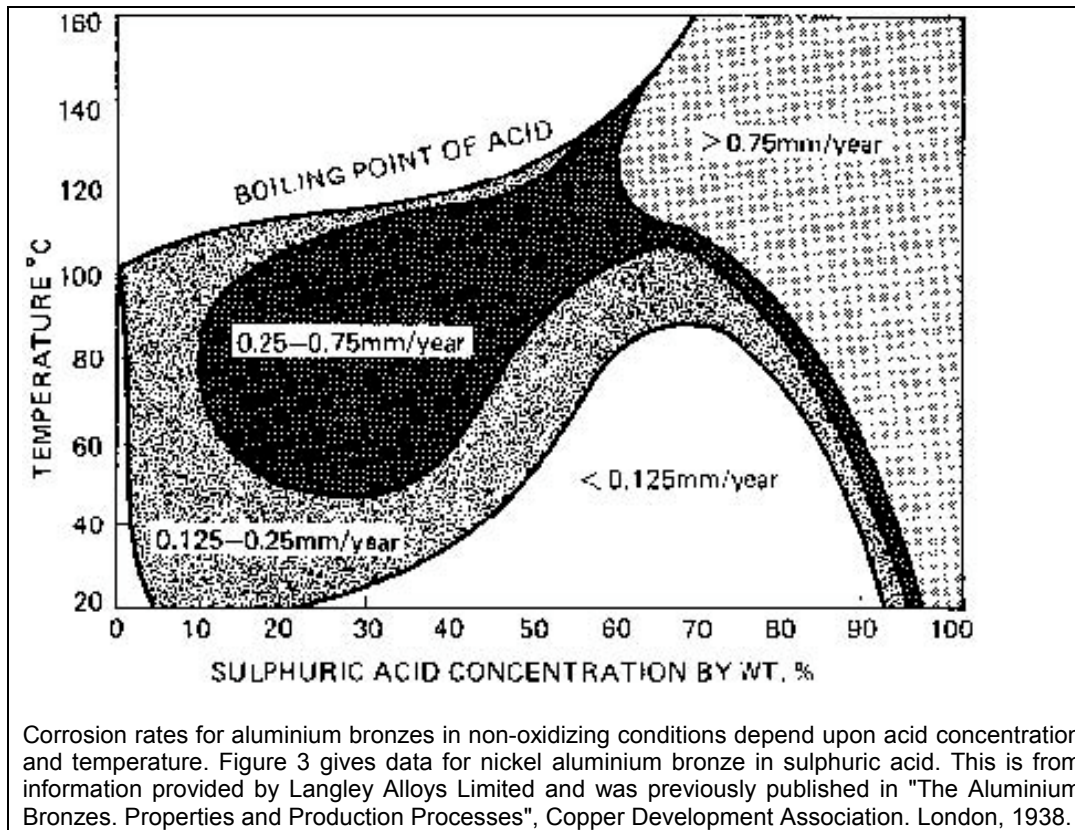
One important application of aluminium bronze in the oil industry is its use for fans in the inert gas protection systems on board oil tankers.

These fans are used to maintain the flow and pressure of the inert gas blanket over the oil cargo so as to obviate the danger of explosion or fire. The inert gas used is produced from the exhaust gas from the main engines, auxiliary engines or sometimes from a special generator, by "scrubbing" with sea water. The fan operating conditions can be very corrosive and far from easy to predict, involving salt-laden water vapour, sulphurous gases and traces of carbon. Several materials have been used to construct the fans, many of which are large and run at high speeds. Only titanium and aluminium bronze have been found to give reliable service and, of these, aluminium bronze is far less expensive. The smaller fans may use cast impellers but the larger ones are fabricated by welding.

iv Specific Corrosive Chemical Environments

The general policy in the chemical manufacturing industries is to construct equipment of mild steel wherever possible and to use stainless steel for those parts where the corrosion resistance of mild steel is inadequate. Copper-base alloys tend to be used mainly in cooling water pumps and valves. Aluminium bronzes are, however, also used for small items in a very wide variety of chemical environments where high resistance to corrosion and erosion are required.

Figure 3 - Corrosion rate of nickel aluminium bronze, CA 104, in sulphuric acid in the presence of oxygen.



Acidic Environments

Aluminium bronzes are often used in processes employing sulphuric acid. Their corrosion resistance depends upon the composition and metallurgical structure of the alloy as well as upon temperature, concentration and degree of aeration or presence of oxidising agents in the acid. Single phase aluminium bronzes generally show the highest resistance to sulphuric acid but alpha-beta alloys are satisfactory provided that they are free from gamma 2 phase. Nickel aluminium bronzes are also satisfactory provided that they are free from retained beta but, unless the higher strength of these alloys is required, a single phase alloy is generally preferred. The effects of temperature and of concentration are not simple and can only be determined experimentally. Figure 3 shows the relationship between temperature, sulphuric acid concentration and corrosion rate for nickel aluminium bronze in the presence of oxygen. Aeration increases the rate of corrosion of aluminium bronzes in sulphuric acid and greater acceleration is caused by the presence of oxidising agents such as ferric salts, dichromates or nitric acid.

The corrosion rate of aluminium bronzes in hydrochloric acid is very much higher than in sulphuric acid and aluminium bronzes are not usually suitable for handling hydrochloric acid solutions (See Table 8). One exception to this general rule is the use of cast AB2 aluminium bronze as pickling hooks for descaling coils of steel wire rod in warm, moderately strong hydrochloric acid. This, however, depends upon the sacrificial cathodic protection which is afforded to the aluminium bronze by the steel.

Table 8 gives corrosion rates for Cu 9%Al in hydrochloric acid. Note that the presence of oxidising agents increases the attack.

Table 8 - Corrosion Rates for Cu. 9%Al in Hydrochloric Acid

Temperature	Additions	% HCl	g/m ² per day
20°C	-	3.6	4 - 5
100°C	-	15	56
100°C	-	30	14
Room temperature	-	30	14
Room temperature	0.8% chlorine	30	42
Room temperature	1% FeCl ₃	30	115

Table 8 is taken from E. Rabald, Corrosion Guide, Second Edition, Elsevier Publishing Company, Amsterdam-London-New York, 1965. Rabald comments "The greater attack at 100°C and 15% HCl is caused by the higher air content" and notes that the solubility of oxygen at 100°C is higher in 15% HCl than in 30% HCl.

Table 9 (also from Rabald) gives corrosion rates in pure 20% and 60% phosphoric acid in long term tests.

Table 9 - Corrosion Rates for Cu 10%Al in Phosphoric Acid mm/year

Temperature	20% H ₃ PO ₄	60% H ₃ PO ₄
15°C	0.06	0.01
50°C	0.10	0.01
75°C	0.25	0.00
bp	-	0.25

The good resistance of aluminium bronzes to corrosion by hydrofluoric acid is exploited in the "frosting" of glass bulbs for electric lamps. Nickel aluminium bronze is used for the nozzles which spray acid into the bulbs and the trays which collect the acid from the process.

Aluminium bronze can be used with other non-oxidizing acids - including most organic acids - and high concentrations of phosphoric and acetic acid have been handled industrially at elevated temperatures. Nitric acid solutions are strongly oxidising and produce rates of attack on aluminium bronze which preclude their use in that environment.

Alkaline Environments

Strongly alkaline environments such as caustic soda or caustic potash solutions remove the protective alumina film from aluminium bronzes and result in steady and moderately high dissolution rates. Less strongly alkaline solutions and moist alkaline chemicals such as sodium or potassium carbonates can be handled satisfactorily. In common with all copper alloys aluminium bronze suffers general corrosion, and shows susceptibility to stress corrosion cracking, in environments containing ammonia.

Table 10 – Uses of Aluminium Bronzes in Corrosive Chemical Environments

Environment	Alloy	Details
Acetic acid 33% at bp.	CuAl8Fe	fPumps, fittings, pipelines, condensers.
Acetic anhydride at bp.	-	fPipelines, pumps, caps for copper stills.
Aluminium fluoride solutions at 100°C.	-	lLinings for reaction vessels producing AlF ₃ from Al(OH) ₃ and HF.
Aluminium sulphate all concentrations up to bp. Free H ₂ SO ₄ present.	-	vValves, pipes, fittings.
Boric acid saturated solutions 105°C.	-	fFittings, filter closures.
Citric acid 33-36% solution up to bp.	-	fFittings, piping.
Dyestuffs, acid dyes.	-	fStirrers, fittings.
Ethylene dibromide up to bp.	-	fPumps.
Fatty acids up to 200°C.	-	vVessels, valves, pumps, vacuum stills.
Fluorine -196 to +200°C.	-	vValve seats.
Fluorosilicates MgSiF ₆ and ZnSiF ₆ at pH 2 120°C.	-	vVacuum evaporators.
Formaldehyde 200 to 400°C.	-	fParts of apparatus for oxidation of MeOH and manufacture of acrolein from HCHO and CH ₃ CHO.
Formic acid room temperature to bp.	CuAl8Fe or CuAl10Fe	fFittings pumps.
Furfural.	-	Autoclaves for manufacture from corn-cobs or straw by acid hydrolysis.
Gelatin up to 100°C.	CuAl5	Boilers for acid and alkaline digestion of skins, bones, etc.
Isobutyl chloride room temperature to bp.	-	Valves, pumps, fittings.
Limonene: mixtures of turpentine with benzoic and salicylic acid 105°C.	-	Valves, pumps, fittings.
Linseed oil.	-	Bottoms of varnish boilers.
Mixed acids 55% H ₂ SO ₄ 40% HNO ₃ , 5% SO ₃ , room temperature.	CuAl10	Bolts for pumps, stuffing boxes.
Molasses room temperature to 180°C.	-	Fittings, valves, piping.
Potassium sulphate all concentrations room temperature to bp.	-	Heating tubes, stirrers, pumps, valves.
Quinine sulphate.	-	Fittings, valves.
Sodium bisulphate all concentrations room temperature to bp.	-	Evaporators, heating coils.
Sodium bisulphites all concentrations room temperature.	-	Blades for beaters in paper industry.
Sodium fluorosilicate 100°C.	-	Evaporators.
Sodium hypochlorite 2% solution room temperature.	-	Knives for hollanders.
Sodium sulphate all concentrations room temperature to bp.	-	Valves, centrifuges, pumps.
Stearic acid room temperature to 250°C.	CuAl8	Vacuum still pans, condensers.
Sulphur dioxide dry or moist bp to 100°C.	-	Valves, pumps.
Sulphurous acid 6% solution room temperature.	-	Piping, valves.
Zinc chloride all concentrations room temperature to 140°C.	-	Vessels, stirrers.
Zinc sulphate all concentrations room temperature to bp.	-	Pumps, piping.

Table 10 presents information taken from E. Rabald, Corrosion Guide, Second Edition, Elsevier Publishing Company, Amsterdam-London-New York, 1968. It lists industrial uses of aluminium bronzes in contact with corrosive chemicals where corrosion rates of < 2.4 g/m² per day (0.008 mm per year) were recorded. The list by no means covers all industrial uses of aluminium bronzes in chemical industry and excludes cases where aluminium bronzes have been used successfully but with corrosion rates somewhat higher than those specified above. The information provided by Rabald does not always include details of the particular aluminium bronzes concerned. Where this is the case, a dash has been inserted under the heading "Alloy" in Table 10.

v Resistance to Atmospheric Corrosion and Oxidation

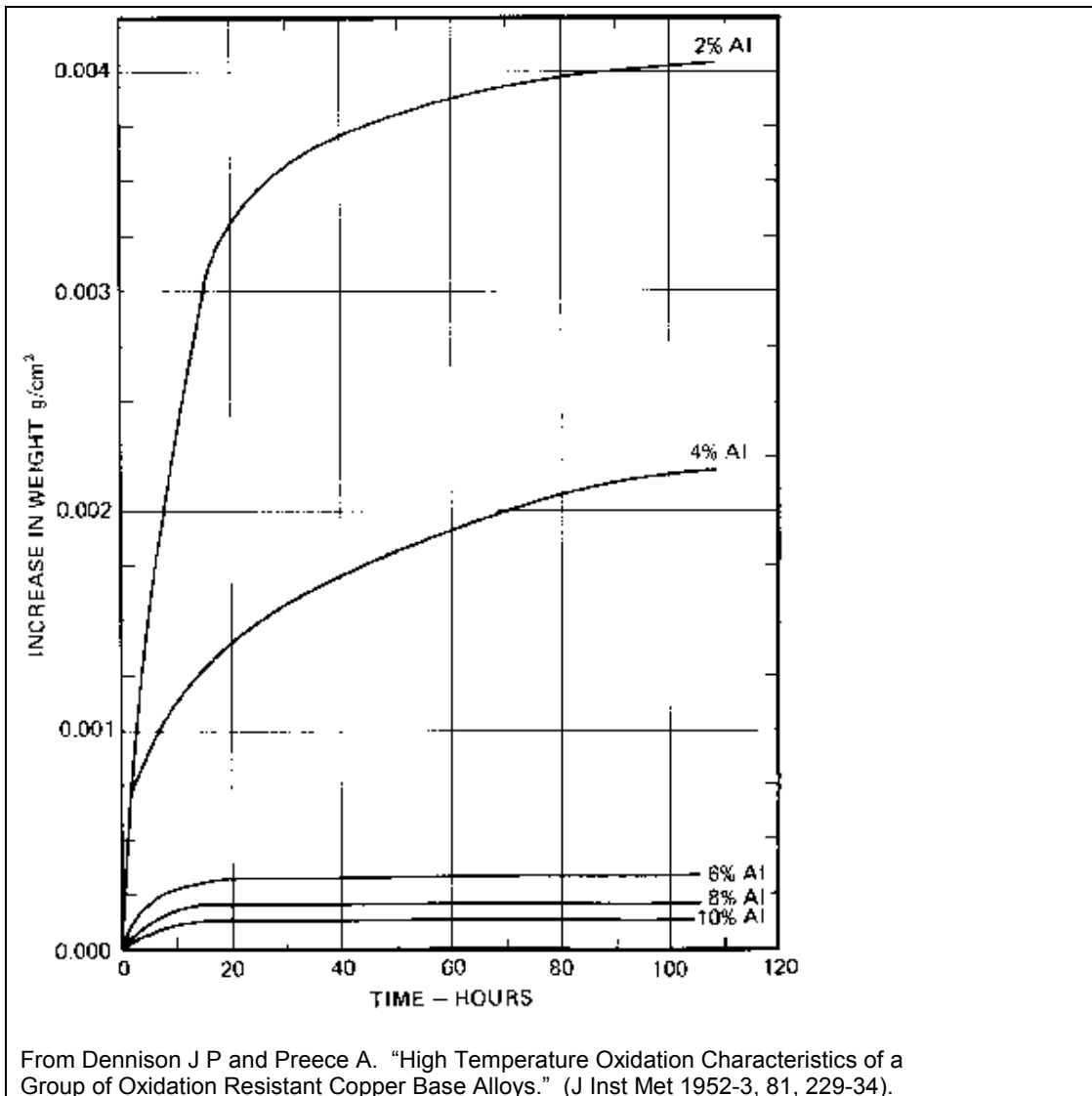
Aluminium bronzes preserve their original golden colour for long periods under normal atmospheric exposure conditions which would produce green patination on copper, brass and most other copper alloys. Little quantitative information is available on the long-term corrosion resistance of aluminium bronzes in the atmosphere but a 7% aluminium, 2% silicon aluminium bronze, similar to UNS 63900, was included in ASTM twenty-year atmospheric exposure tests commenced in 1957. The final results have yet to be published, but after seven years, this alloy showed average corrosion rates lower than those of any other copper alloys tested.

The high resistance of aluminium bronzes to atmospheric corrosion combined with their ability to carry heavy loads at low rubbing speeds without undue wear or distortion makes them particularly suitable for bearing bushes in aircraft frames. Nickel aluminium bronze, CA104, is widely employed for this purpose.

Sulphur dioxide pollution is an important cause of corrosion of most metals under atmospheric exposure conditions and, as noted in Section 4(iv) the resistance of aluminium bronzes to sulphuric acid is high. It is not, therefore, surprising that aluminium bronze is used for access fittings for high chimneys. Another very important property of aluminium bronzes for this purpose is their low susceptibility to stress corrosion cracking. The high-temperature oxidation resistance of aluminium bronze results from the formation of a thin protective aluminium oxide film and increases with the aluminium content of the alloy. Figure 4 shows that the improvement in oxidation resistance over

copper is most marked as the aluminium content is increased to about 6% - further increase of aluminium content above that level producing relatively little further improvement.

Figure 4 - The influence of aluminium content on the oxidation of copper-aluminium alloys at 650°C



vi Aluminium Bronzes in Building

The combination of high strength with good general corrosion resistance and low susceptibility to stress corrosion cracking presented by aluminium bronzes make them a preferred material for load bearing masonry fixings. For fixings made from wrought rod or sections the best alloy is CA104; the corresponding cast alloy AB2 is generally used for cast fixings and sockets though AB1 is sometimes employed.

The appearance and tarnish resistance of aluminium bronzes make them suitable for decorative architectural features but their relatively high price compared with brasses and high tensile brasses limits their use for this purpose. A specialized application for aluminium bronze in building is as reinforcement bars or clamps used in the repair of old stonework. Restorations of stonework carried out in the nineteenth century were commonly made using cast or wrought iron for reinforcement and subsequent rusting of the reinforcement has resulted in severe further damage to the stonework. Aluminium bronze is the most suitable of the copper alloys for this purpose, not only because of its high resistance to general corrosion and to stress corrosion cracking but because its high strength enables bars and clamps of relatively small section to be used, with correspondingly less damage to the old stonework during installation of the reinforcement.

Table 11A – Compositions of Aluminium Bronzes in Common Use: Wrought Alloys

Alloy Type	Designation					Composition % ⁽¹⁾												
	B.S.	D.G. Ships	UNS/ASTM	DIN	ISO 428	Al	Fe	Ni	Mn	Si	Sn	Pb	Zn	Other				
CuAl	CA101		60600 60800	CuAl5	CuAl5	4.5–5.5	–	–	–	–	–	0.02	–	–				
						4.0–7.0	0.5	–	–	–	–	–	–					
						5.0–6.5	0.10	–	–	–	0.10	–	As 0.35					
	CA102						60600 60800	CuAl5	CuAl5	4.0–6.0	0.4	0.8	0.3	0.3	–	0.02	0.5	As 0.4
										4.0–6.5	0.5	0.8	0.5	–	–	0.1	0.5	As 0.4
										6.0–7.5	Fe + Ni + Mn 1.0–2.5 (optional)			–	–	–	–	–
CA103		60600 60800	CuAl5	CuAl7 CuAl8	6.5–7.5					0.5	0.8	0.5	–	–	0.1	0.5	–	
					7.5–9.0					0.5	0.8	0.5	–	–	0.1	0.5	–	
8.8–10.0					Fe + Ni 3					–	0.10	0.05	0.40	Mg 0.05				
CuAlFe					CA106		61400 ⁽²⁾ 62300	CuAl8Fe CuAl10Fe CuAl10Fe3	6.5–8.0	2.0–3.5	0.5	0.5	0.15	0.10	0.05	0.40	–	
									6.0–8.0	1.5–3.5	–	1.0	–	–	0.01	0.20	P 0.015	
									6.5–8.5	1.5–3.5	1.0	1.0	–	–	0.05	0.5	–	
	6.5–9.0	1.5–3.5	0.8	0.8					0.2	0.2	0.02	0.5	–					
	8.0–10.0	2.0–4.0	–	–					0.25	0.20	–	–	–					
	9.0–11.0	1.5–4.0	1.0	1.5–3.5					0.2	0.5	0.05	0.5	–					
CuAl-FeSn			61300	CuAl7Fe3Sn	6.0–8.0	3.5	–	–	–	0.20	–	–	–					
					6.0–8.0	1.5–3.5	1.0	1.0	–	0.15–0.50	–	–	–					
CuAlNiFe	CA104	1043 ⁽³⁾	63200	CuAl10Ni	CuAl10Ni5Fe4 CuAl9Fe4Ni4	8.5–11.0	4.0–6.0	4.0–6.0	0.5	0.10	0.10	0.05	0.40	Mg 0.05				
						8.5–10.0	4.0–5.5	4.0–5.5	0.5	0.10	0.10	0.05	0.40	Mg 0.05				
						8.5–9.5	3.0–5.0	4.0–5.5	3.5	0.10	–	0.02	–	–				
	CA105					62800 ⁽⁵⁾ 63000	CuAl10Ni	CuAl10Ni5Fe4 CuAl9Fe4Ni4	8.5–11.0	2.0–5.0 ⁽⁴⁾	4.0–6.0 ⁽⁴⁾	1.5	–	–	0.05	0.5	–	
									8.5–10.5	2.5–5.3	3.0–6.0	1.5	0.2	0.2	0.05	0.5	–	
									8.0–11.0	2.5–4.5	2.5–5.0	3.0	0.1	0.2	0.1	0.5	–	
									8.5–10.5	1.5–3.5	4.0–7.0	0.5–2.0	0.15	0.10	0.05	0.40	Mg 0.05	
									8.0–11.0	1.5–3.5	4.0–7.0	0.5–2.0	–	–	–	–	–	
									9.0–11.0	2.0–4.0	4.0–5.5	1.5	0.25	0.20	–	0.30	–	
CuAlSi	1044 ⁽⁶⁾	63900	CuAl7Si2	6.0–6.4	0.5–0.7				0.10	0.50	2.0–2.4	0.10	0.01	0.40	Mg 0.05			
				6.5–8.0	0.1				0.25	–	1.5–3.0	–	0.05	–	–			
				6.0–7.6	0.8				0.25	0.1	1.5–2.5	0.2	0.05	0.5	–			

Table 11B – Compositions of Aluminium Bronzes in Common Use: Cast Alloys

Alloy Type	Designation					Composition % (1)								
	B.S.	D.G. Ships	UNS/ASTM	DIN	ISO 1338	Al	Fe	Ni	Mn	Si	Sn	Pb	Zn	Other
CuAlFe	AB1		95200 95300	G-CuAl10Fe	CuAl10Fe3	8.5–10.5	1.5–3.5	1.0	1.0	0.25	0.1	0.05	0.5	Mg 0.05
						8.5–9.5	2.5–4.0	–	–	–	–	–	–	
						9.0–11.0	0.8–1.5	–	–	–	–	–	–	
						8.5–11.0	2.0–4.0	2.5	1.0	0.20	0.30	0.20	0.50	
						8.5–11.0	2.0–3.0 ⁽⁷⁾	3.0	1.0	0.20	0.30	0.20 ⁽⁸⁾	0.40	
CuAlNiFe	AB2	348	95800	G-CuAl9Ni G-CuAl10Ni	CuAl10Fe5Ni5	8.8–10.0	4.0–5.5	4.0–5.5	1.5	0.10	0.10	0.05 ⁽⁹⁾	0.50	Mg 0.05
						8.9–9.6	4.0–5.0 ⁽¹⁰⁾	4.5–5.5 ⁽¹⁰⁾	1.0–1.4	0.10	0.10	0.02	0.2	Mg 0.05
						8.5–9.5	3.5–4.5 ⁽¹¹⁾	4.0–5.0 ⁽¹¹⁾	0.8–1.5	0.10	–	0.03	–	–
						7.8–9.8	4.0–6.0	4.0–6.5	1.5	0.10	0.20	0.10	0.30	–
						8.8–10.8	4.0–6.0	4.0–6.5	1.5	0.10	0.20	0.10	0.30	–
						8.0–11.0	3.5–5.5	3.5–6.5	3.0	0.10	0.20	0.10 ⁽⁸⁾	0.50	–
CuAl-Si		129	95600			6.0–6.4	0.5–0.7	0.10	0.50	2.0–2.4	0.10	0.01	0.40	Mg 0.05
						6.0–6.4	0.5–0.7	–	2.0–2.4	–	–	–	–	–
CuMn-Al	CMA1					7.5–8.5	2.0–4.0	1.5–4.5	11.0–15.0	0.15	1.0	0.05	0.50	P 0.05
	CMA2					8.5–9.0	2.0–4.0	1.5–4.5	11.0–15.0	0.15	1.0	0.05	0.50	P 0.05

- (1) Single values are maxima.
- (2) Formerly known as Alloy D.
- (3) Formerly known as 8452.
- (4) Ni-content higher than Fe-content will assist in preventing corrosion.
- (5) Formerly known as Alloy E, now replaced by 63000.
- (6) Formerly known as 8453.
- (7) May be reduced to 1.0% for permanent mould castings.
- (8) 0.02% if castings are to be welded.
- (9) 0.01% if castings are to be welded.
- (10) Nickel must exceed iron.
- (11) Fe content shall not exceed Ni content.

Copper Development Association

5 Grovelands Business Centre

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