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Collation of Data Comparing Properties of Aluminium Bronze with Cast Stainless Steels and Ni-Resist in Offshore Sea Water Environments

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EXECUTIVE SUMMARY

Aluminium bronzes have a long and successful history of use in seawater, it is the standard material specified for ships' propellers and is preferred for seawater systems in submarines. Many workers have studied the corrosion resistance of aluminium bronzes, others have studied ferrous materials. Few workers have studied both simultaneously and comparisons were not readily available.

To help materials selection and value-for-money decisions, this publication has been prepared, financed by Copper Development Association, International Copper Association and the Association of Bronze and Brass Founders. The work reported was carried out by Dr J W Oldfield and Dr G L Masters of Cortest Laboratories Limited.

This project has collated data comparing the properties of cast nickel aluminium bronze (NAB), in particular NES 747 Part 2, with cast standard and super austenitic and duplex stainless steels and Ni-Resist for use in offshore sea water applications. Properties compared are physical, mechanical and fabrication but the bulk of the work has related to the corrosion aspects of the materials.

Corrosion properties compared are general corrosion, pitting, resistance to polluted sea water, crevice corrosion, erosion corrosion, cavitation, stress corrosion cracking, corrosion fatigue and galvanic corrosion. An overall composite ranking for the corrosion resistance has been established showing the superduplex stainless steels to be the best followed by the superaustenitic alloys with NAB close behind in third place. The standard duplex, Ni-Resist and standard austenitic stainless steels make up the six.

Within this composite ranking,

- Nickel Aluminium Bronze stands up well against superduplex alloys in terms of general corrosion, pitting, cavitation and corrosion fatigue.
- A pitting resistance temperature indicator (CPT or PREN) is not relevant to aluminium bronze since it is not susceptible to this type of corrosion.
- Its erosion corrosion, although not as good as superduplex alloys, is reasonable;
- It is immune to chloride stress corrosion cracking.
- It has comparable strength to the austenitic materials and can, by heat treatment have properties comparable to the duplex alloys.
- The alloy has excellent heat transfer and electrical conductivity properties as well as good wear resistance and anti fouling properties.
- Its weldability is considered comparable with superduplex stainless steels.
- NAB should not be used in polluted sea water containing sulphides.
- It is cheaper than most stainless steels.

Overall, providing the price of cast nickel-aluminium bronze is significantly lower than cast superduplex or superaustenitic stainless steels, there are many applications where it can compete successfully, based on cost linked with corrosion properties. Typical examples of these applications are rising mains for fire hydrants, pumps and valves, desalination equipment and sea water valves for submarine applications.

From a technical point of view these marine applications would use the major strengths of NAB compared particularly with superduplex stainless steel. These are:

Good general corrosion resistance
Good pitting corrosion resistance
Reasonable erosion corrosion resistance
Comparable resistance to cavitation and fatigue
Immune to chloride stress corrosion cracking (SCC)
Comparable strength
Good weldability
Excellent heat and electrical transfer properties
Excellent wear resistance
Much superior anti-fouling properties

1.0 INTRODUCTION

Cortest were commissioned by CDA to conduct a collation of data comparing the properties of aluminium bronze with cast stainless steels and Ni-Resist in sea water environments as part of an ABBF/ICA project to develop new markets for aluminium bronze.

2.0 BACKGROUND

2.1 General

Aluminium bronzes have been well established for many years with an excellent reputation for corrosion resistance in marine environments. Castings are used to make pumps, valves pipe fittings and similar items for use in marine, offshore and submarine applications. These are vital components in seawater systems where the tubing may also be of aluminium bronze but is more frequently copper-nickel or other material. The alloy is strong, ductile, machinable and readily weldable. It makes sound intricate castings if good foundry practice is used. Aluminium bronze components are also used with stainless tubing for seawater systems where chlorine injection is used.

In recent years, cast stainless steels, particularly duplex stainless steels, have been heavily promoted for service in the offshore sea water market. Aluminium bronzes have lost some market share. In order to address this situation, a project 'Developing New Markets for Aluminium Bronze' has been instigated. Phase I of this project includes the objective 'To establish a definitive technical and operational status for aluminium bronze castings in comparison with alternative casting materials used in offshore sea water environments'. The method of approach to complete this objective was :

a) To assemble all existing data from all possible sources on the properties of materials used for castings in offshore environments.
b) To assemble this data in a logical and usable format which readily allows comparisons and rankings to be made for all relevant properties.

2.2 Materials and Properties

It was agreed that the properties of the cast nickel-aluminium bronze similar to BS 1400 AB2 but as more closely specified in Naval Engineering Standard NES 747, would be compared with those of four types of cast stainless steel, namely type 316, the 6Mo 'superaustenitic' alloys, the duplex alloys generally known as '2205' and the 'superduplex' alloys, as well as the austenitic nickel cast iron Ni-Resist D2-W. Information was sought on four categories: physical properties, mechanical properties, corrosion properties and fabricating properties. The draft spreadsheet produced by CDA comprising a list of specific properties was used as a check list.

3.0 SOURCES OF DATA

3.1 Nickel Aluminium Bronze

The corrosion-resistant properties of aluminium bronze have been well summarised by Campbell for CDA (see NAB reference 16). It was decided that in conjunction with Cortest's own data sources, and those supplied by CDA, an on-line literature search offered the optimum method for identifying relevant information on this material. A computerised search of the METADEX database was therefore commissioned. METADEX provides comprehensive coverage of international metals literature, including references to approximately 1,200 primary journal sources from 1968 to the present. Using the search word ALUMINIUM-BRONZE, the database identified 1,050 references. The search string CASTING OR CORROSION produced 126,102 references. The common set of these two search parameters consisted of 354 references, for all of which hard copy of the abstracts was obtained. Twelve references not already held on file by Cortest appeared particularly relevant, and full copies of these were obtained; a list of references for these papers, and others considered relevant, is given in Appendix 1. These papers were analysed for relevant data.

In addition to the literature search, trade catalogues and literature were requested from the ABBF member foundries, namely:

F W Birkett
Hanson Foundry
Meigh Castings
Spunalloys
Westley Brothers

3.2 Cast Duplex Stainless Steels

Cortest has extensive experience of, and information on, duplex stainless steels, including the proceedings of two major duplex stainless steel conferences held in Beaune 1991 and Glasgow 1994. Relevant information has been extracted from these and other sources. These include wrought and cast alloy producers.

3.3 Cast Austenitic Stainless Steels

The majority of information on austenitic stainless steels originates from Inco databooks and more recently Nickel Development Institute (NiDI) publications as well as from Cortest's in-house library. However very little of this relates to cast materials, although some aspects of welded materials are covered by references listed in Appendix 1. In addition to this, information was sought direct from wrought alloy producers and, where known, foundries. A list of foundries is given in Appendix 2.

3.4 Ni-Resist Cast Iron

There is a range of Ni-Resist alloys for a variety of applications. Much information is available on these from Inco databooks and, more recently, NiDI publications. The alloy of particular interest to this study is Ni-Resist Type D2-W, a ductile, weldable grade which is recommended for corrosion applications, particularly sea water service. Relevant references on Ni-Resist are listed in Appendix 1. In addition information was sought direct from foundries; a list of foundries is given in Appendix 2.

4.0 GENERAL OVERVIEW OF PROPERTIES

4.1 Alloy Compositions

4.1.1 Nickel Aluminium Bronze

The cast nickel aluminium bronzes are covered by ASTM B148-93a as UNS C95800 and by the British Standard 1400:1985 as AB2. The Naval Engineering Standard (NES) 747 (superseding DGS 348) includes AB2 (NES 747 Part 3) subject to a tighter limit on lead. NES 747 Part 2, on the other hand has tighter compositional limits than AB2, which together with a specified heat treatment of 675°C ± 15°C for a minimum period of 6 hours before cooling to room temperature in still air, results in a different structure, giving it superior corrosion properties. It is the preferred material for severe sea water conditions and is therefore the alloy considered in this report. The bulk chemical compositions of BS1400:1985 AB2 and NES 747 Part 2 are given in Table 1.

(Note that NES 747 Part 1 is the same material as NES 747 Part 2, except that it is centrifugally cast).

The level of impurities and some minor elements are significantly different in the two alloys and this is illustrated below:-

IMPURITIES (max.)

Element	NES 747 Pt2	AB 2
Zn	0 .05	0.50*
Pb	0 .01	0.03
Si	0 .10	0.10
Sn	0 .05	0.10
Mg	0 .05	0.05
Cr	0 .05	NS+
Total impurities allowed	**0.25 max**	**0.30 max (excl Zn)**

* Note that Zn in not a designated impurity in AB2
\+ NS = not specified

These data highlight the much tighter tolerances of NES 747 Pt 2 compared with AB2. It should also be noted that NES 747 Pt 2 has to be made from virgin material or in-house returns of known composition and origin. If AB2 castings are within specification, their performance is satisfactory.

4.1.2 Cast Duplex Stainless Steels

4.1.2.1. Alloy 2205

This is a wrought material with the common name '2205'. It is specified by UNS No. 31803, and the DIN Werkstoffe No. 1.4462. As a wrought material it offers an alternative combination of strength, weldability, corrosion resistance and low cost; it competes successfully with type 316 stainless steels in many applications, especially tube and pipe. The demand for matching castings has led to the production of castings from this alloy (UNS J92209). With good practice in melting, moulding, casting, heat treating and welding excellent properties can be achieved. However, the alloy is not easily castable. Segregation of alloying elements reduces pitting and crevice resistance, and the low Cr content gives a low nitrogen solubility which may lead to porosity in castings. Also, as with all duplex stainless steels, the good weldability is lost when the section increases , in castings as well as in forgings. Increasing the Cr content to 25% makes the alloy much easier to cast, with increased corrosion resistance. Thus the equivalent cast grade giving the same or slightly better corrosion resistance as wrought 2205 is 26Cr - 6Ni - 3Mo -N. The proprietary material Ferralium is typical of this type of alloy.

4.1.2.2. Superduplex Stainless Steels (SDSS)

The term 'superduplex' was coined to be the duplex equivalent of the term 'superaustenitic'. The term 'super' related originally to material with good enough corrosion resistance to withstand ambient temperature, untreated sea water. Wrought versions include Zeron 100 (UNS S32760) and SAF 2507 (UNS S32750). The cast equivalent of Zeron 100 is specified by UNS J93380.

The bulk tonnage of superduplex stainless steels is produced and used as wrought products, predominantly as sheet, plate, pipe and tube. Castings are a necessary and vital supplement in most applications. Typical castings are for pumps and various armatures. These are joined to the wrought parts either mechanically or by welding.

While from a design point of view the wrought and cast part should be of the same alloy, the different production process calls for a modification of the alloy composition.

The different production methods result in certain differences in the product which are reflected in a somewhat different service performance. They are:-

(i) The grain size in the casting is coarser than in the mechanically deformed wrought structure, resulting in more pronounced microsegregations in the cast structure with potential differences in corrosion behaviour.

(ii) The properties in castings are isotropic while they are anisotropic in wrought products. Depending on design, machining and service conditions this can be an advantage or disadvantage. The use of high purity materials possible by modern melting methods minimises the effect of impurities on corrosion properties.

(iii) The N content in a cast alloy is restricted. The lower effective N solubility on slow cooling in the mould, the possible N or C pick up from the sand mould, or metal-mould reactions involve the risk of porosity formation, limiting the N level typically to 0.25%.

(iv) Casting sections usually are in the range of cm rather than mm as in most wrought products. Therefore, it is more difficult to avoid precipitates and segregation during heat treatment or welding. However, in wrought products of similar section, the same problems occur. This should be borne in mind when comparing corrosion resistance of castings with thin section sheet or tube.

Each of the generic duplex stainless steel types is produced under specific brand names by different manufacturers. These vary slightly in composition between manufacturers; typical compositions of different alloys in each class are given in Table 1.

4.1.3 Cast Austenitic Stainless Steels

4.1.3.1. Type 316 Stainless Steel

Wrought type 316 stainless steel (UNS No. S31600) together with 316L, the low C weldable grade (UNS No. S31603), have for many years been considered the 'corrosion resistant' grades of stainless steel for a variety of applications. Because of their general high usage, cast versions of both alloys have also been produced for many years under the casting standard designations CF-8M and CF-3M respectively. These alloys have very similar composition to the wrought versions; sometimes slightly lower Ni levels are allowed to aid castability. Typical compositions are given in Table 1. As with all castings segregation effects can result in a corrosion resistance which is inferior to the wrought product.

4.1.3.2. 6% Mo Superaustenitic Stainless Steels

The development of the wrought version of these alloys started in the mid 1970s with Inco's development alloy IN748. This led to Allegheny Ludlum's 'AL6X', which initially had problems with sigma formation. This was followed by Avesta's 254SMO alloy (UNS S31254 wrought, UNS J93254 cast); further developments then followed with Krupp VDM's 1925hMO (UNS NO8926) and Allegheny's AL-6XN (UNS N08367). All these and other similar alloys, contain approximately 6% Mo, 20% Cr and 18 - 25% Ni with N and sometimes other minor additions. Nowadays, users consider them all to have the same corrosion resistance, although this is not always the case. The composition of some of these alloys is given in Table 1.

The development of these alloys took some considerable time, as did their welding. In fact welding of these alloys is usually carried out with the nickel base alloy 625, which has much higher corrosion resistance than the base metal. This gives an indication of the potential problems than can occur in trying to cast these alloys. Cast versions of the alloys are available, but not readily so; certainly there does not seem to be the experience of casting that is available with the superduplex alloys.

4.1.4 Ni-Resist Cast Iron

Ni-Resist is an austenitic nickel cast iron. Nickel has a graphitising effect on cementite, producing a grey iron. Nickel also acts as a grain refiner, preventing coarse grains forming in slow cooling heavy sections. It also toughens thin sections, which might otherwise be liable to cracking. Magnesium, contained in Type 2, converts graphite from flakes to spheroids, providing ductility and impact resistance. Ni-Resist castings are widely used in corrosive environments to withstand attack from dilute acids and alkalis. Type D2 (ductile) Ni-Resist is recommended for service requiring resistance to corrosion, erosion, frictional wear, and temperatures up to 750°C. This type also has high thermal expansivity. Type D2-W is a modification of the D2 grade, the W indicating improved weldability. This is achieved by a small addition of Niobium and controlling the basic composition by reducing the Phosphorus and Magnesium contents. The alloy is quite widely used for sea water applications; its composition is given in Table 1.

4.2 Physical Properties

Typical properties of the various alloy families are given in Table 2.

It can be seen that the densities of the stainless steels are slightly higher than that of aluminium bronze; any significant weight savings in components are therefore due to superior properties allowing smaller sections.

The coefficient of thermal expansion of NAB is similar to that for the austenitic stainless steels. The duplex stainless steels have a slightly lower coefficient of thermal expansion. Thermal conductivity of NAB is 2 to 3 times that of the stainless steels. Its' electrical conductivity is also considerably higher.

The wear resistance of NAB is excellent and it is frequently used as a bearing material. Also, because of its high Copper content it has much superior anti fouling properties compared with the ferrous materials.

4.3 Mechanical Properties

4.3.1 Ambient Temperature

Typical mechanical properties at ambient temperature, are shown in Table 3. NES 747 has a specified heat treatment of 675 ± 15°C for a minimum period of 6 hours before cooling to room temperature in still air. This gives the specified mechanical properties. AB2 has a wider permitted variation in composition (particularly Al). It may be heat treated to give higher yield and tensile strengths e.g. 925°C heat treatment followed by a water quench and temper at 625°C to give mechanical properties that may even exceed those of superduplex. The tempering temperature was developed initially to give a material microstructure more resistant to corrosion than the 'as cast' form. It gives an optimum finely divided precipitate of alpha and kappa, with all the martensitic beta phase dissociated. Corrosion resistance is therefore good, but accurate information comparing the effects on corrosion resistance of this heat treatment with that now specified in NES 747 is lacking. After welding, it is good practice to solution anneal NAB for two hours at 700-720°C to remove retained beta.

The Young's modulus of duplex stainless steel at 200 GPa exceeds that of NES 747, 130 GPa (Young's modulus for duplex stainless steels is a function of austenite/ferrite ratio and production route. Variations of ±5% are found with both wrought and cast duplex products).

4.3.2 Temperature

Mechanical properties decrease at elevated temperature as shown in Table 4. It can be seen that superduplex stainless steel is the only alloy to have superior properties to NES 747 Part 2 at 200°C and above.

It should also be noted that nickel aluminium bronze retains strength and ductility at low temperatures and is a suitable material for cryogenic applications.

4.4 Corrosion Properties

In contrast to the physical and mechanical properties which are fairly well defined, much of the corrosion data quoted in the literature has been generated under a range of different conditions. Therefore direct comparison between the alloys is not always best presented in tabular form. For stainless steels in particular there is little information available on cast as opposed to wrought material. In general terms the corrosion resistance of cast stainless steels is at best equal to, but maybe somewhat inferior to the wrought material. For all the alloys quantitative data is given where possible, together with a general assessment to each form of corrosion. It should also be remembered that service conditions vary considerably, and while a material may not normally be susceptible to a particular form of attack, a change in condition (e.g. raised temperature) may lead to a critical situation where corrosion may occur. There is also some overlap between the different forms of attack; data may therefore appear under more than one heading.

4.4.1 General Corrosion in Sea Water

General corrosion is not usually considered a problem for NAB in quiescent sea water. Corrosion rates 0.06 mm yr^{-1} are reported for AB2 in static (<0.5 m s^{-1}) sea water (NAB ref.17). Al-Hashem et al (NAB ref.13) reported a corrosion rate of 0.1mm/y for ASTM B148-93a, UNS C95800 in quiescent sea water. They reported that the alpha phase was attacked selectively at the interface with the intermetallic kappa precipitates. The kappa precipitates and the precipitate free zones did not suffer corrosion. It is worth noting here that Rowlands (NAB ref.19) showed that at pH ~8.2 the kappa phase is cathodic to the alpha phase causing the alpha phase to corrode and this agrees with these findings. At lower pH values of around 3 that can develop in crevices the alpha phase becomes cathodic to the kappa phase resulting in preferential attack of the kappa phase. Thus, any corrosion of NAB in quiescent sea water whether of a general nature or in crevices takes the form of selective phase attack. It should be noted that NES 747 Pt 2 was developed to minimise the formation of kappa precipitates and in particular to break up continuous networks of their precipitates. In this way the susceptibility to selective phase attack is significantly reduced. Stainless steels do not suffer general corrosion under these conditions.

Taylor Group literature states that Ni-Resist vertical fire pumps on North Sea oil rigs have been examined after ten years service showing corrosion amounting to less than 3 mpy (0.08 mm y^{-1}). Charts give corrosion rates of ductile Ni-Resist D-2 in sea water as a function of temperature. These show that up to 40^{o}C, Ni-Resist corrodes at a fairly constant rate of 0.02 mm y^{-1} in de-aerated sea water and 0.2 mm y^{-1} in aerated conditions. Craig et al (Ni-Resist ref.6) reported a general corrosion rate of 0.9 mpy (0.02 mm y^{-1}) for type 2 Ni-Resist in stagnant de-aerated sea water and 1.7 mpy (0.04 mm y^{-1}) in aerated conditions.

Thus in summary, the stainless steels are not susceptible to general corrosion; Ni-Resist corrodes at an acceptably slow rate whilst the general corrosion of NAB is not considered a significant problem.

4.4.2 Pitting Corrosion

Pitting corrosion is a localised form of attack resulting from the breakdown of a protective film on an alloy. In sea water NAB and Ni-Resist do not suffer from this form of attack. Stainless steels on the other hand, which rely on a thin protective 'passive film' for their corrosion resistance, can be susceptible.

There are a range of tests used to assess a stainless steel's resistance to pitting corrosion, perhaps the most common is the critical pitting temperature (CPT) test whereby the highest temperature at which pitting does not occur is determined. This test is usually carried out in a ferric chloride solution but other solutions have been used.

Another common method of assessing pitting resistance is to calculate the Pitting Resistance Equivalent Number, PREN for the alloy. There are various 'expressions' for this but the most common is:-

$$PREN = (\% Cr) + 3.3 (\% Mo) + 16 (\% N)$$

An alternative version has higher nitrogen (N) coefficient of 30 rather than 16. Table 5 gives the PREN values for both N coefficients and for the range of alloy composition within the specification for the stainless steels under consideration in this project. A value of 40 or above is usually considered to indicate satisfactory resistance to pitting in sea water environments. Thus the superaustenitics and superduplex alloys generally do not suffer pitting in sea water at ambient temperature. Both 316 stainless steel and the duplex alloy 2205 are, however, susceptible.

It should be noted that the CPT test and the PREN number relate to resistance to the initiation of pitting and say nothing about the propagation rate of attack. This can be important and it is worth noting that in general the rate of propagation on duplex materials can be significantly greater than on austenitic materials.

In summary, in ambient temperature, clean sea water only 316 stainless steel and the duplex alloy 2205 are susceptible to pitting corrosion. The higher alloyed stainless steels, NAB and Ni-Resist are not susceptible to this form of attack.

4.4.3 Polluted Sea Water (containing Hydrogen Sulphide)

Hydrogen sulphide is produced when organic matter decays. This occurrence results in one common form of polluted sea water. The sulphide ion is damaging to all the materials under consideration here with the exception of Ni-Resist. The degree of damage varies but the presence of sulphide results in a very much reduced corrosion resistance for all Copper-base alloys, including NAB.

NAB corrodes at an increased rate in sulphide-contaminated sea water due to a change in the structure of the passivating layer by incorporation of copper sulphide (CuS) (NAB ref.5). The cuprous oxide and aluminium oxide, responsible for passivation are replaced by a highly porous corrosion product consisting largely of copper sulphide (CuS). CuS markedly accelerates the charge transfer reaction of oxygen reduction, which occurs on the surface of the corrosion layer. As a consequence the overall corrosion is entirely cathodically controlled and depends sensitively on the high flow velocities prevailing in practical application. The formation of oxide phases needed for repassivation does not take place at a sufficient rate. The corrosion of NAB in sulphide-polluted sea water reported by Schüssler and Exner appears to be of a general or pitting nature.

On stainless steels the presence of sulphide ions tends to reduce the stability of the passive layer resulting in a reduced resistance to localised attack such as pitting and crevice corrosion. Very high levels of sulphide result in an iron sulphide film which acts in a protective way. In applications under consideration here it is lower levels of sulphide which are considered relevant. As in clean sea water 316 stainless steel and the 2205 duplex alloy are again susceptible to attack. For the superaustenitic and superduplex alloys their corrosion resistance is reduced somewhat but evidence to date indicates that they are not susceptible to significant corrosion under these conditions.

Where copper alloys are required for use in environments that may sometimes be sour it is common to specify tin bronze (CT1) for impellers and leaded gunmetal (LG4) for pump cases.

4.4.4 Crevice Corrosion

Crevice corrosion is a term used for corrosion occurring in a region where ready solution access is not available; typical crevices are flanges, fasteners, debris etc. With the exception of Ni-Resist all the alloys under consideration here are susceptible to some degree.

Any crevice corrosion on nickel aluminium bronze takes the form of minor selective phase de-alloying. In this phenomenon, an electrochemically active phase is preferentially corroded, often followed by the redeposition of copper. Since the corroded phase is depleted of Aluminium, this form of attack is often termed dealuminification. The effects are therefore related to metallurgical structure and in general the reported depth of attack is minimal.

Stainless steels are also susceptible to crevice corrosion in sea water. In general the more highly alloyed, pitting-resistant materials are also more resistant to crevice corrosion. The large influence of very small differences in crevice gap on attack makes comparison between different sets of data difficult. Nevertheless crevice corrosion has been the subject of many studies. In general in sea water 316 stainless steel and the 2205 duplex material are susceptible to attack.

The higher alloyed stainless steels, in many crevice situations, are resistant at ambient temperature but even under these conditions, if the crevice geometry is very severe e.g. a threaded joint, attack can occur. In less severe crevices, as the temperature is increased and/or chlorination has been carried out the resistance to attack is reduced and corrosion initiation will occur.

In summary, 316 stainless steel and the 2205 duplex alloy are susceptible to crevice corrosion in ambient temperature sea water. The higher alloy stainless steels become susceptible as crevice geometry becomes severe, and as the temperature increases and chlorination is applied. Ni-Resist is not susceptible to this form of attack. NAB suffers selective phase attack in crevices but depth of attack is minimal.

4.4.5 Erosion Corrosion

Erosion corrosion or impingement attack takes place under flowing conditions. The flow generates a shear stress which results in damage to the protective layer on the material and this results in corrosion. Stainless steels have a very thin adherent protective passive film which is not susceptible to this form of attack. Thus these alloys can be used at very high velocities and even at 40ms^{-1} no corrosion is observed.

The nickel aluminium bronzes are generally considered to have excellent resistance to flowing sea water due to the rapid self-repair of the protective oxide film. However, Ault (NAB ref.14) found that the corrosion rate of UNS C95800 varied logarithmically as a function of the velocity of fresh unfiltered sea water over the range 25 to 100 fps. The minimum rate was 0.5mm y^{-1} at 25 fps (but with areas of non-uniform corrosion of up to 2mm y^{-1} in some areas) rising to 0.76mm y^{-1} at 100 fps. The higher flow rates showed uniform corrosion evidenced by a smooth, polished appearance after exposure. Cathodic protection to -0.6V vs silver - silver chloride essentially prevented corrosion at both low and high flow rates.

Table 6 shows erosion corrosion rates for DGS348 (now NES 747) in sea water jet impingement tests at fairly high velocities (NAB ref.16). The influence of temperature can be seen. In general 4.3m/s (14 ft/s) is taken as a design limit for NAB. Like NAB, Ni-Resist is susceptible to erosion corrosion and, at 14.5ft s^{-1} for example corrosion rates of 0.27mm y^{-1} and 0.02mm y^{-1} have been found in aerated and deaerated sea water respectively.

In summary the stainless steels are not susceptible to this form of attack. NAB has a nominal design limit of 14ft s^{-1} whilst Ni-Resist corrodes at a significant rate in aerated sea water at this velocity.

4.4.6 Cavitation Corrosion

Cavitation can be defined as the growth and collapse of vapour bubbles resulting from localised pressure changes in a liquid, and is associated with components that are driven at high velocity through a fluid (i.e. propellers and pumps). The bubbles are formed in the liquid in regions of very low pressure, for example behind the leading edge of a propeller blade. Rapid collapse of the bubbles produces a strong wave, damaging the material. The stresses are often sufficient not only to remove protective corrosion product films but actually to tear out small fragments of metal from the surface by fatigue.

All the alloys under study in this project are reported to have extremely good resistance to cavitation. NAB for example is commonly used for the production of large marine propellers and high duty pump impellers, Ni-Resist is also reported to be suitable for these applications. Thus this form of attack is not of great concern when dealing with these materials.

4.4.7 Chloride Stress Corrosion Cracking

Stress corrosion is a highly localised form of attack occurring under the simultaneous action of tensile stress and an appropriate environment. Although the total amount of corrosion may be small, cracking occurs in a direction perpendicular to that of the applied stress and may cause rapid failure. Internal stresses due to welding or cold work may be minimised by a stress relief heat treatment.

Couture (NAB ref.1) reports that NAB exhibits no tendency to chloride stress corrosion cracking (SCC) in sea water. Therefore where high service stresses are unavoidable, the low susceptibility of NAB to SCC can be exploited.

Stainless steels on the other hand are susceptible to chloride SCC but there are significant differences in resistance between the various alloys. 316 material is most susceptible and in sea water SCC can occur above 80-100°C; for the superduplex materials the lower temperature range is 100-150°C. For the duplex alloys these ranges are somewhat higher, 120-150°C for alloy 2205 and 150-200°C for the superduplex alloys. Thus, so long as only low temperature applications are considered this form of attack is not of concern for stainless steels.

Ni-Resist is, on the other hand, susceptible to SCC in ambient temperature sea water and therefore in all such applications it must be stress relieved.

4.4.8 Corrosion Fatigue

There is not much published literature available on corrosion fatigue in sea water. Sedricks data (NAB ref.18) shows that, percentage wise, there is the same fall off in strength over quite a wide range of materials. Thus the higher strength materials also have higher fatigue strength. In this regard NAB, which can have a high strength, has a good corrosion fatigue strength.

4.4.9 Galvanic Corrosion

Galvanic corrosion is attack which occurs when two dissimilar metals or alloys which are far apart on the 'galvanic series' are connected together. A typical example is stainless steel connected to steel in sea water; the stainless steel accelerates the corrosion of the steel and, in turn, the steel offers cathodic protection to the stainless steel.

Table 7 shows the potentials of the various alloys under consideration in natural, ambient temperature sea water. The austenitic stainless steels are the most noble with Ni-Resist being the most active. NAB is more active than the austenitic materials and marginally more active than the duplex alloys. These facts should be taken into account in any mixed alloy sea water system. However it is clear that NAB should not cause any problem that are not also of concern for the duplex alloys.

4.4.10 Summary of Corrosion Properties

In this section the six categories of materials have been reviewed in terms of resistance to nine types of corrosion. An attempt to collate all this information in a semi-quantitative manner is summarised in Table 8. Each alloy has been allocated an arbitrary ranking number between 0 and 10 for each type of corrosion. In Table 8 galvanic corrosion has not been included since, within the scope of the exercise, it is not possible to distinguish the materials resistance to this form of attack.

From Table 8 we see that for overall corrosion resistance the following ranking is obtained.

Superduplex stainless steel	72
Superaustenitic stainless steel	68
Nickel aluminium bronze	66
Duplex 2205 alloy	60
Ni-Resist	57
316 stainless steel	53

This is believed to gives a fair reflection of the overall relative merits of the six alloy types from a corrosion viewpoint. Study of Table 8 will show the variations likely to be found under different service conditions. For example, if use in polluted seawater is eliminated from consideration, nickel-aluminium bronze ranks significantly higher.

4.5 Fabrication Properties

SG Ni-Resist type D-2, subject to compositional control and Nb addition in grade D-2W, can be repair welded. Most welding is concerned with the reclamation of castings. For this purpose, the processes available are usually limited to manual arc welding with flux-coated electrodes and the occasional use of oxy-acetylene welding.

The welding of nickel aluminium bronze castings is commonly used for the assembly of components difficult to produce as a single casting, and to rebuild worn components during overhaul. Nickel aluminium bronze castings may also be welded (NAB ref.16) to repair small areas containing porosity. In sea water service, selective phase dealloying of the alpha phase immediately adjacent to the lamellar kappa sometimes occurs in the outer regions of the HAZ of welds in NAB. The attack is sometimes accelerated by the presence of internal stresses in the casting which produces cracking in the porous redeposited copper, increasing the rate of penetration of attack. Welded NAB 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 it cooling rapidly from temperatures at which conversion to alpha-plus-kappa begins. Beta phase may also be reformed from the alpha-plus-kappa in the HAZ of parent metal nearest the weld. Heat treatment of welded NAB prevents the majority of these problems. The treatment used is the same as the NES 747 Pt 2 cycle.

Low carbon versions of type 316 stainless steel have been developed to allow ease of welding of castings. The high alloy austenitic materials are weldable using material similar to the nickel base alloy 625. This results in welds with superior corrosion resistance to the base metal.

Welding of the wrought 2205 duplex and superduplex alloys has been the subject of much development over the past decade. It appears that problems initially encountered, particularly with welding super duplex materials, have now been solved, although care has to be taken and detailed procedures followed. These techniques can be transferred to castings.

5.0 PRICE OF CASTINGS

Although some comparative prices were obtained in this exercise, it was not possible to compare accurately and like for like for various commercial reasons. Prices vary significantly and are dependant not only on metal mixture cost but pattern making, foundry techniques and finishing costs. Casting techniques, including section thicknesses and running and gating systems, vary for each material and patterns have to be modified accordingly.

An estimate of the relative ranking, based on price, for the six categories of materials, is given below.

High price	Superaustenitic stainless steel
	Super duplex stainless steel
⇑	2205 duplex
	Nickel aluminium bronze
⇓	316 stainless steel
Low price	Ni-Resist

One rule of thumb guide that was suggested is that while aluminium bronze and 316 may be broadly similar in price, castings in superaustenitic stainless steel can cost nearly twice as much. Actual prices are of course variable according to casting size, intricacy, specific alloy composition and of course the special expertise of foundries concerned.

6.0 COMMERCIAL IMPLICATIONS

This collection of data has concentrated on corrosion resistance of the six types of material under consideration whilst taking some account of their physical and mechanical properties together with their ease of welding. To establish the real commercial implications these data have to be linked with detailed cost comparisons between castings of the six types of alloy. This data is not readily available and in its absence the alloys have simply been ranked on price in a qualitative way. This ranking is based on our own estimates.

As one might expect the alloys with the overall higher corrosion resistance also have the highest price, namely the superduplex and superaustenitic stainless steels. The corrosion resistance of NAB, in an overall way, is not far behind these alloys; its physical and mechanical properties compare well with the competing materials. Its weldability is good but perhaps not as good as the austenitic stainless steels. Thus, providing its price is significantly less (say 20% or more) than the super austenitic and superduplex alloys there are applications where it can compete successfully with the high alloyed stainless steels e.g. rising mains for fire hydrants, pumps and valves, desalination equipment and sea water valves for submarine applications.

From a technical point of view these marine applications would use the major strengths of NAB compared particularly with superduplex stainless steel. These are:

- Good general corrosion resistance
- Good pitting corrosion resistance
- Reasonable erosion corrosion resistance (for a Cu base alloy)
- Comparable resistance to cavitation and fatigue
- Immune to chloride SCC
- Comparable strength
- Excellent heat and electrical transfer properties
- Excellent wear resistance
- Much superior anti-fouling properties

The weaknesses of the material, which should therefore be avoided are:

- Reduced corrosion resistance in polluted sea water
- Susceptibility to selective phase attack

7.0 SUMMARY AND CONCLUSIONS

This project has collated data comparing the properties of cast nickel aluminium bronze (NAB) with cast standard and super austenitic and duplex steels and Ni-Resist for use in offshore sea water applications. Properties compared are physical, mechanical and fabrication but the bulk of the work has related to the corrosion aspects of the materials.

Corrosion properties compared are general corrosion, pitting, resistance to polluted sea water, crevice corrosion, erosion corrosion, cavitation, stress corrosion cracking, corrosion fatigue and galvanic corrosion. An overall composite ranking for the corrosion resistance has been established showing the superduplex stainless steels to be the best followed by the superaustenitic alloys with NAB close behind in third place. The standard duplex, Ni-Resist and standard austenitic stainless steels make up the six. Within this composite ranking NAB stands up well against superduplex alloys in terms of general corrosion, pitting, cavitation and corrosion fatigue. Its erosion corrosion, although not as good is reasonable; it is immune to chloride stress corrosion cracking. With regard to other properties it can have comparable strength and has excellent heat transfer and electrical conductivity properties. It has excellent wear resistance and anti-fouling properties. Its weldability is considered comparable with superduplex stainless steels. NAB should not be used in polluted sea water containing sulphides.

Overall, providing the price of cast NAB is significantly lower than cast superduplex or superaustenitic stainless steels, applications are available based on cost linked with corrosion properties.

Table 1: Alloy Compositions (wt%)

Ni-Al BRONZE	Cu	Al	Fe	Ni	Mn	Impurities
AB2 BS1400:1985	bal	8.8-10.0	4.0-5.5	4.0-5.5	3.0 max	0.20 excl Zn
NES 747 Part 2	bal	8.8-9.5	4.0-5.0	4.5-5.5*	0.75-1.3	0.25 total

* Ni must exceed Fe

STAINLESS STEELS							
Grade	**Form**	**Cr**	**Ni**	**Mo**	**N**	**C max**	**other**
Duplex							
UNS S31803	Wrought	21-23	4.5-6.5	2.3-3.5	0.08-0.2	0.03	1.0Cu max
UNS J92205	Cast	21-23.5	4.5-6.5	2.5-3.5	0.1-0.3	0.03	
Superduplex							
UNS S32760	Wrought	24-26	6-8	3-4	0.2-0.3	0.03	0.5-1.0W 0.5-1.0Cu
UNS S32750	Wrought	24-26	6-8	3-4	0.24-0.32	0.03	
UNS J93380	Cast	24-26	6.5-8.5	3-4	0.2-0.3	0.03	0.51-1.0W 0.5-1.0Cu
Type 316							
UNS S31600	Wrought	16-18	10-14	2.3	-	0.08	
UNS S31603	Wrought	16-18	10-14	2.3	-	0.03	
UNS J92900 (CF-8M)	Cast	18-21	9-12	2-3	-	0.08	
UNS J92800 (CF-3M)	Cast	17-21	9-13	2-3	-	0.03	
Superaustenitic							
UNS N08367	Wrought	20-22	23.5-25.5	6-7	0.18-0.25	0.03	0.75Cu max
UNS S31254	Wrought	19.5-20.5	17.5-18.5	6-6.5	0.18-0.22	0.02	0.5-1.0 Cu
UNS N08926	Wrought	20-21	24.5-25.5	6-6.8	0.18-0.20	0.02	0.8-1.0 Cu
UNS J93254	Cast	19.5-20.5	17.5-19.7	6-7	0.18-0.24	0.025	0.5-1.0Cu

Ni-RESIST	Fe	Ni	Cr	Si	C	Mo	other
D2-W **	**bal**	**18-22**	**1.5-2.2**	**1.5-2.4**	**3.0 Max**	**0.5-1.5**	**Nb 0.12-0.2 P 0.05 max Mn 0.5-1.5 Cu 0.5 max**

** Controlled close compositions for welding

Table 2: Physical Properties

	NES 747 Part 2	Duplex SS	Super-duplex SS	Type 316 SS	Super-austenitic SS	Ni-Resist D2 - W
Density/g cm^{-3}	7.5	7.9	7.8	8.0	8.0	7.4
Thermal conductivity W m^{-1} K^{-1} at 20°C	33-46	14	12.90	15	13.5	13.4
Specific heat capacity J kg^{-1} K^{-1}	419	NA	460-500	470-500	500	NA
Coefficient of thermal expansion 10^{-6} K^{-1}	16.2	13	13	16.5-18.5	16.5	18.7
Electrical resistivity µ ohm m	0.19-0.25	NA	0.916	0.75	0.85	1.02

Table 3: Mechanical Properties at Ambient Temperature

	NES* 747 Part 2	Duplex SS	Super-duplex SS	316 SS	Super-austenitic SS	Ni-Resist D2-W
0.2% Proof stress N/mm^2	250 min	415 min	450 min	240 min	250 min (290 typ)	241 (D2)
Tensile strength N/mm^2	620 min	620 min	700 min	530 min	550 min (650 typ)	407 (D2)
Elongation %	15-20	NA	25	50	35 - 50	7
Young's modulus/GPa	124-130	200	180- 200	200	200	113-128 (D-2)
Hardness (HB)	140-180	187	285 max	156	155 typ	160-200

Note : for AB2, with a water quench from 925°C and with a selected temper 0.2% proof stress values up to 440 N/mm^2 can be achieved. However this might affect the corrosion properties and further investigative studies are required in this regard.

Table 4: Mechanical Properties at Elevated Temperature

	Temp °C	NES 747 Part 2	Duplex SS	Super duplex SS	316 SS *	Super austenitic SS	Ni-Resist (type D2)
Proof stress N/mm^2	100	250	415	380	240	210	240
	149				201		
	200	232	NA	350		170	
	260				172		
	316	221					
	371				159		
	425						193
Tensile strength N/mm^2	100	685	620	650	530	600	400
	149				517	NA	
	200	522	NA	600			
	260				503		
	316	469		500			
	371				500		
	400	296					
	425						372

* annealed sheet

Table 5: Pitting Resistance Equivalent (PREN) for stainless steels

	Duplex SS	Superduplex SS	316 SS	Superaustenitic SS
$PREN_1$	**30.9-39.9**	**37.1-44**	**24.6-30.9**	**42.2-47.4**
$PREN_2$	**32.5-44.7**	**40.3-48.8**	**24.6-30.9**	**45.1-51.3**

$PREN_1 = (\%Cr) + 3.3\ (\%Mo) + 16(\%N)$
$PREN_2 = (\%Cr) + 3.3\ (\%Mo) + 32(\%N)$

Table 6: Erosion Corrosion Attack of cast DGS 348 (NES 747) in Jet Impingement Tests

(at 9.3 ms^{-1} (ref 16))

T/°C	Attack at Jet	
	diameter/mm	depth/mm
10	**0**	**0**
15	**10**	**0.12**

Table 7: Corrosion Potentials of Materials in Ambient Temperature Sea Water

Alloy	mV vs SCE
Nickel Aluminium Bronze	**-175 to -225**
Duplex Stainless Steel	**-100 to -200(E)**
Super Duplex Stainless Steel	**-100 to -200(E)**
Type 316 Stainless Steel	**- 0 to -100**
Superaustenitic Stainless Steel	**+50 to -50**
Ni-Resist	**-450 to -550**

E = Estimate

Table 8: Summary of Corrosion Properties

(In these arbitrary values, 10 ranks highest)

	Nickel Aluminium Bronze	Duplex Stainless Steel	Superduplex Stainless Steel	316 Stainless Steel	Superaustenitic Stainless Steel	Ni-Resist
General Corrosion	9	10	10	10	10	8
Pitting Corrosion	10	5	9	4	9	10
Crevice Corrosion	8	4	8	3	8	10
Erosion Corrosion	8	10	10	10	10	6
Cavitation	8	8	8	8	8	5
Stress Corrosion	10	9	9	8	8	5
Polluted Sea Water	4	5	9	4	9	7
Corrosion Fatigue	9	9	9	6	6	6
TOTAL SCORE	66	60	72	53	68	57

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Appendix 2 Steel Foundries Approached

Westcroft Castings Ltd
Ingersoll Rand Sales Co
Dresser Rand UK
Firth Vickers Centrispinning
PS plc Forges Foundries & Engineering (Renishaw Foundry)
Taylor Group
Goodwins Steel Castings Ltd
Lennox Foundry
Darwin Alloy Castings Ltd
Lloyds (Burton) Ltd
KSB
David Brown Pumps
William Cook Group
DHI Technology
Hopkinsons Ltd

Also information sought from

Avesta Sheffield
Weir Materials
Scana Staal
Allegheny Ludlum
Inco