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Cast Valve Materials for Seawater Service:
Nickel-aluminium Bronze and its Rivals

J R C Strang, Shipham Valves

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Seawater, corrosion, nickel-aluminium bronze, pressure-temperature ratings, stainless steel, 6Mo, duplex, super duplex, nickel alloys, titanium.

Abstract

Nickel-aluminium Bronze (NAB) has been used for seawater service for many years. It is also widely recognised that it is excellent at this. However, with the pressures on either purchase cost reduction or minimum through-life cost, it often appears to sit uncomfortably between the cheapest solution (cast irons) at the low end and the more expensive super duplex, nickel alloys and titanium at the other. The aim of this paper is to show that the NAB solution is cost effective, avoiding the poor performance of the low-end materials and the extreme expense of the high-end ones.

There are very few comparisons of materials that cover the full range of material options, from standard to titanium, including the copper alloys, and the duplex stainless steels. This paper will provide comparisons covering mechanical properties, performance in various corrosion conditions as well as costs associated with valve manufacturing. The review will draw on Shipham's extensive experience of manufacturing valves in most of the materials considered, as well as making reference to published literature from a variety of sources.

The materials include cast iron, carbon steel, 316 stainless, 6Mo, duplex and super-duplex stainless steels, nickel alloys and titanium as well as a selection of high performance nickel-aluminium bronzes. The common corrosion types will be covered.

Additionally, the pressure-temperature characteristics of Nickel-aluminium Bronze will be discussed. On the one hand, everyone knows that Class 150 has a maximum operating pressure of "about 20 bar" and some are aware that for bronze alloys there is a maximum of 15.5 bar. The truth lies somewhere between these two limits. There is no standard that both maximises the potential of NAB as well as recognising its limitations, enabling an economic and a safe design.

In conclusion, NAB is shown to be particularly useful for seawater service, despite elevated temperature and sulphide environment limitations. The main advantages are that:

- It is cheaper than the exotic stainlesses, and so cost effective;

- Its performance on general corrosion, pitting and cavitation is comparable to superduplex alloys and significantly better than the standard alloys;
- It also has beneficial properties of good heat conduction, does not gall, and has excellent anti fouling properties, and
- It can have a pressure temperature rating well above the bronze standards.

An extensive bibliography is included, enabling further research or investigation if required.

1 Introduction

Bronze, the combination of copper and tin, is an ancient material as is implied by the term “Bronze Age”, which is sometime after the Stone Age but before the Iron Age, perhaps as long ago as the 4^{th} millennium BC. The name bronze can be considered a handicap for the aluminium bronzes, perhaps due to these ancient associations and that an immediate comparison is made with the inferior copper-tin alloys.

In the above context, aluminium bronze is a modern introduction. The combination of copper and aluminium first took place in the mid 1800’s. It was very expensive to produce and consequently, other than being an object of investigation for metallurgists, was not much used. At the turn of the century, additional alloying elements were being investigated and in 1913 Durville perfected his tilting ladle process to make aluminium bronze billets. This “Durville Process” was necessary to overcome the problem of shrinkage defects and oxide inclusions characteristic of the alloys, partially due to the narrow freezing range. This was so successful that the French government used the alloy (Cu 9Al) for a range of coins (50 centimes, 1 & 2 Francs).

Charles H Meigh developed this process further and worked with the French Admiralty to produce an early nickel-aluminium bronze (Cu 10Al3Ni3Fe3Mn). Further investigations by metallurgists saw the development of the alloys and its common commercial usage grew with the requirement for ship’s propellers suitable for increasing speeds. As Meigh (2000, xxix) states “… nickel-aluminium bronze (NAB) is twice as resistant to corrosion fatigue as manganese bronze and stainless steel …”, it has become the most popular material for this use. Growth in the oil industry and the need, initially for seawater fire pumps, has also spread the use of NAB. Navies have also used NAB extensively, where its strength and weldability replaced gunmetal (Cu SnPbZn). It is thought that the loss of the US nuclear submarine *Thresher* in 1963, due to a casting failure, hastened the uptake of NAB for use on submarines. (Meigh, 2000)

More recently, with the advent of super austenitics and various duplex stainless steels, the trend has been towards these newer materials, or even in some cases to the more exotic and expensive titanium. In 1986 copper-nickel pipe seems to have been well established together with NAB valves. For reasons of weight, strength and velocity limitations (erosion damage in the Cu-Ni pipe above 3.5 m/s) the newer materials were considered. For example, a 20” CuNi diameter pipe could be replaced by a 14” 254 SMO material. (Gallager, Mallpas & Shone, 1986). Subsequent experience of these materials, has shown that there are temperature limitations and cost implications with casting quality control. This paper serves as a reminder of the benefits of NAB and suggests that there is still a place for NAB valves between the extremes of the low cost and exotic alternatives.

2 Nickel-aluminium Bronze: What is it?

While aluminium bronze (without the nickel) is used, the most popular alloy, certainly for valve applications is the duplex alloy of around 8% - 11% of aluminium with the addition of iron and nickel to give higher strength and correctly known as nickel-aluminium bronze. Unfortunately, this is often and confusingly abbreviated to aluminium bronze. In order to simplify matters, only NAB will be considered here. Alloys are available in both cast and wrought form. A summary of the main cast alloys is:

American	ASTM B148	UNS C95800	Nominal Cu bal 9Al 4.5Ni 4Fe 1.2Mn
		UNS C95500	Nominal Cu bal 11Al 4Ni 4Fe
European	EN 1982	CC333G	Nominal Cu bal 10Al 5Ni 5Fe

Mention must also be made of the still popular (although the standard is obsolete) BS1400 AB2 and the British Navy specification DEF STAN 02-747 and the equivalent wrought specification DEF STAN 02-833. These alloys are all similar with detail differences hinging on the introduction of manganese and the balance between iron and nickel.

The mechanical properties will be considered later, but these NAB alloys are considered as high strength. As engineers know, high strength is not everything and ductility is a significant factor. In this instance the trade-off is between C95500 with 6% elongation and a minimum tensile strength of 620 MPa and C95800 with 15% and 585 MPa respectively.

An overview of general properties of the material is that it is weldable, castable and has an outstanding corrosion resistance due to a tough oxide film. Shock and wear resistance is also excellent (variants of the material can be used as bearings) and it is also non-sparking and has a low relative magnetic permeability (for near-zero relative magnetic permeability combined with excellent corrosion properties, aluminium-silicon bronze can be used). The conductivity, both electrical and thermal, is also very good. Additionally NAB retains its strength and ductility at low temperatures and is suitable for cryogenic service.

Considering properties in isolation is all very well, but it is only when comparisons with “rival” materials are made that performance can be properly evaluated. The mechanical and corrosion properties will therefore be discussed comparatively in the next sections.

3 Mechanical Properties

Selecting a range of materials for comparison and simplifying the comparison by taking a representative alloy from each group, standard-specified properties of tensile and yield strength are shown in *Figure 1.* The alloys chosen are detailed in Appendix I.

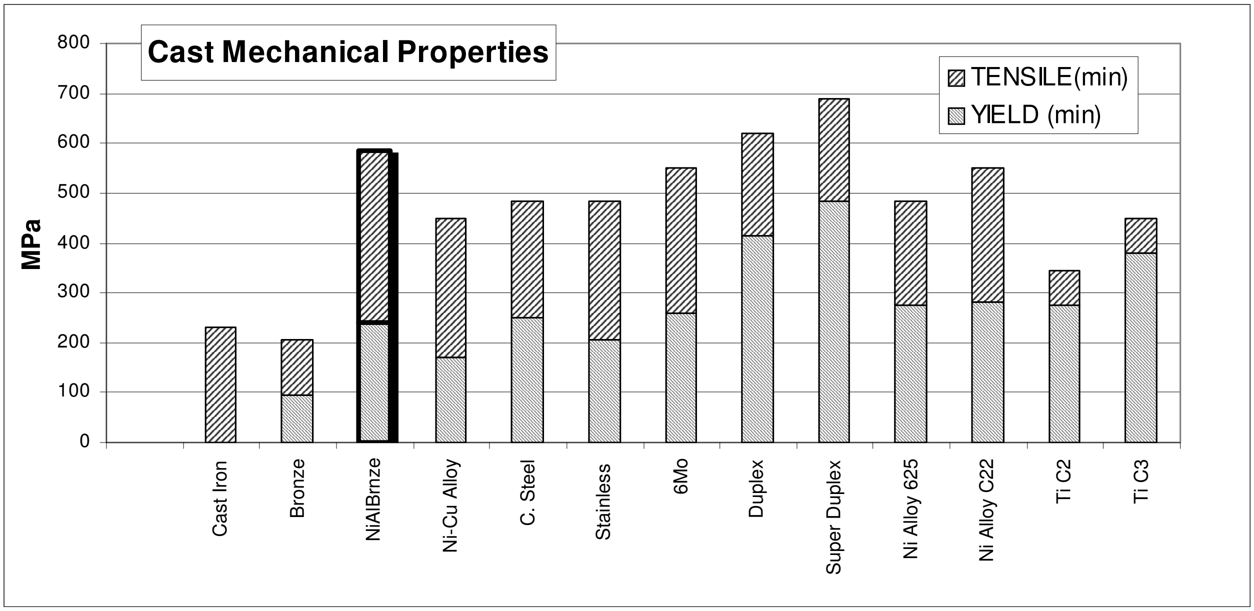

Figure 1: Mechanical Properties of Selected Cast Alloys

Figure 1 illustrates several points clearly. First, the difference between "bronze" and NAB is dramatic. This shows that the association by the fact of being a copper alloy and sharing the tag of bronze can damage the reputation of NAB. The yield strength of NAB is over double that of bronze (also known as gunmetal or valve bronze).

Second, perhaps more surprisingly, is that NAB's mechanical properties are better than those of Ni-Cu alloy (more popularly known as Monel®). While there are high strength Ni-Cu wrought alloys such as K-500, the common cast alloys do not perform so well, as is illustrated.

Third, the common carbon and stainless steels materials do not differ significantly as far as the base mechanical properties are concerned. In fact, the mechanical properties of NAB are only significantly exceeded by the duplex and super-duplex materials.

In terms of valves, the mechanical properties are not a determining factor. In order to assist standardisation of dimensions, flange and valve standards generally adopt a philosophy of specifying a standard set of dimensions for a pressure class and then identifying a pressure-temperature rating associated with these dimensions and a particular group of materials. The pressure-temperature rating then becomes the all important factor. The rating is based on the mechanical properties, but also takes account of the performance at varying temperatures. So the true comparison is between the ratings of the different materials.

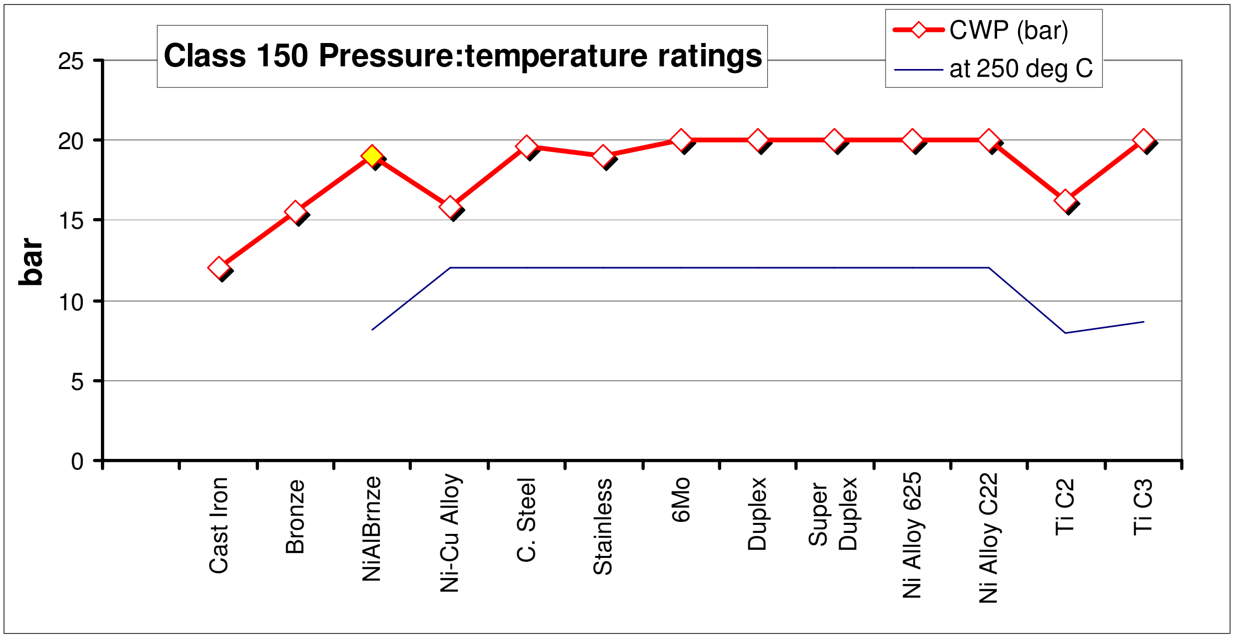

Figure 2: Comparative pressure - temperature ratings

Figure 2 shows the cold working pressure (CWP) for the various materials. The comparison is not straightforward because the bronze and cast iron figures relate only to flat-face flanges and all the other dimensions relate to the ANSI B16.5 raised face dimensions. This fact will be discussed in more detail later as will the fact that the NAB and titanium ratings have been specially calculated.

A comparison between the pressure-ratings and the mechanical properties shows that the difference between the various materials has been flattened. The way the ratings are determined imposes an upper limit on the pressure, a ceiling is applied in order to limit deflection. The materials affected by this ceiling figure are 6Mo, the duplexes and Ni alloys.

For comparison, the rating at 250°C is included. This illustrates the shortcomings of copper alloys at raised temperatures. Whilst there is no rating for bronze, NAB is less than most of the other materials, as are the titanium's. The maximum temperature and pressure for each material is given in *Appendix II*. The difference between materials is further reduced by the use of ceiling values at higher pressures.

Mechanically, NAB can be seen to compare well enough to compete with its rivals. There is a limitation once high temperature performance is considered, however this is not generally an issue for seawater service.

3 Corrosion Comparison

Corrosion is a complex topic with many variables, down to the precise chemical constituents of a material and its heat treatment. This is further complicated by the infinite possible service conditions. The medium itself is only one element, the environment, pressure, temperature, flow-rate are others that can have a significant effect. Even limiting consideration to seawater is not straightforward as this varies geographically and is also affected by biological activity. The large oil companies invest significantly in metallurgy and corrosion control – it is interesting to observe the effect of company culture on metallurgical decisions: there is a line in the North Sea, to the left of which bronze is suitable for hydrants, but to the right only titanium will do! This shows that there are many solutions to similar problems.

What follows is a broad generalisation and is intended to be helpful as an overview. It is drawn from a variety of sources, most of which are listed in the bibliography (*Appendix IV*). It is frustrating that although much has been written and researched on comparative corrosion, it is inevitable that the comparison that you are searching for is not available directly, so a certain degree of extrapolation is necessary. Inevitably the conditions compared are different – often it is difficult to tell if this is significant or not. The following summary aims to be helpful by being giving a general picture, however the specifics in any particular situation should always be considered.

3.1 General corrosion

Most of the materials considered do not have a problem with general corrosion – except for carbon steel and cast iron where protection in the form of coating is required.

3.2 Pitting & Crevice Corrosion

Pitting is a localised form of attack in quiet seawater, resulting from non-uniformities in the environment. This is a significant differentiating factor between the materials considered. Tests giving a critical pitting temperature (CPT) or a calculation to assess the pitting resistance to chloride pitting and crevice corrosion for stainless steels, the pitting resistance equivalent number (PREN= %Cr +3.3x%Mo + {16 or 30}x%N) can be used. These will give an indication of pit initiation, rather than pit propagation. Worst affected are the steels, as the alloys become "higher" the problem disappears. It is worth noting that pit propagation on duplexes can be more severe than on austenitic materials, and that pitting and crevice corrosion resistance of 22Cr duplex in waters containing high levels of chloride is poor. Precautions are advised in the case of contact with untreated seawater (Smith, Celant & Pourbaix, 2000; HSE Safety Notice 3/2003, Norsok M-001).

NAB is not considered to be affected by chloride pitting, attack in crevices is minimal and is reported to show no tendency to chloride stress corrosion cracking. (Oldfield and Masters, 1996)

3.3 Velocity effects

The types of corrosion covered here are erosion-corrosion, cavitation and impingement at higher velocities and fouling from marine organisms at low flows.

Fouling occurs when marine organisms attach themselves to the material. Due to differential aeration effects, this sets up a corrosion cell. Copper alloys are considered to be good in this situation as copper is inhospitable to many of the organisms. Ni-Cu has some fouling resistance and the remaining alloys have a very low resistance. (Tuthill & Shillmoller, 1965)

As velocity increases, the flow of oxygen to the metal surface is increased and this can has a significant effect on corrosion rates. Galvanising extends life only by about 6 months on carbon steel (Todd). Higher flow rates, particularly if the flow medium contains abrasive particles can also strip off protective oxide films. This is the case with copper alloys where there are velocity limitations. Sources vary in what these limits are, but 4.3 m/s is frequently quoted as the limit for NAB with a recommendation of 10 m/s as an intermittent maximum, (Norsok M-001) whereas 23 m/s is a guideline for the peripheral velocity of pumps and propellers (Tuthill, 1987).

3.4 Temperature

In general, temperature will accelerate the rate of any chemical reaction, so corrosion processes take place more quickly. However, raised temperatures also leads to a lower oxygen content which can have the opposite effect. The effective corrosion rate is therefore a balance between these two factors. This is significant for the crevice corrosion of stainless and duplex stainless steels where a limit of 20 ^{o}C is recommended for 6 Mo, 22Cr & 25Cr materials in seawater applications with crevices. (Norsok M-001, with maximum free chlorine of 1.5 ppm). Other temperature recommendations are minimum temperatures of –46 ^{o}C for 22Cr, -30 ^{o}C for 25Cr and in seawater maxima of 15 ^{o}C with crevices and 30 ^{o}C without crevices. (Tystad, 1997).

As can be expected, the corrosion processes are accelerated in NAB, but no particular adverse effects are noted.

3.5 Galvanic Considerations

Galvanic corrosion results from the connection of two different metals by an electrolyte, such as seawater. The corrosive effect is in proportion to the distance apart on the galvanic series, or the difference of the potentials of the two materials. This effect is significant and the reason why valve material is frequently determined by the selection of the piping material. Relative exposed areas are highly relevant.

In general NAB is more anodic than the other materials considered (except for carbon steel, cast iron and bronze) and is therefore more likely to corrode in contact with the other materials. This is emphasised by the recommendation that NAB should not be coupled with 25Cr in natural seawater (Francis, 1999).[1]

Dissimilar materials can also be chosen to maximise protection. One such case is the use of NiCu alloy trim with NAB body material. The NiCu is protected and the large surface area of the NAB ensures that the corrosion goes unnoticed.

3.6 Other Corrosive Conditions

NAB should not be used in polluted seawater conditions due to the presence of hydrogen suphide. Precautions are also advised for duplex materials (Smith et al, 2000; Norsok M-001).

In general, NAB is good in acidic environments, but as strongly alkaline environments

[1] However, if the temperature is less than 25 ^{o}C and the seawater is chlorinated, corrosion can be suitably controlled in the NAB as the 25Cr behaves differently. The chlorine prevents the formation of a biolfilm making the stainless steel a much less efficient cathode. (Francis, 1999)

remove the protective film, corrosion rates in this case can be high.

3.7 Corrosion Summary

Building on earlier work (Oldfield and Masters, 1996), the tables in *Figure 3* and *4* are a summary of the relative corrosion of the materials considered. The scale is arbitrary and is intended to convey the overall performance of the various materials under the appropriate headings. It is useful if the scale is used as intended, a ranking system, rather than a detailed comparison (10 does not mean twice as good as 5). Although not corrosion, wear and galling performance has been added. The excellent NAB properties in this area make the life of valve designers and users significantly easier.

Rather than identify an overall winner, the strengths and weaknesses of the various materials are identified. None of these properties can be properly considered without a view of the costs and intended life as well.

Arbitrary scale, higher is better	*General Corrosion*	*Pitting Corrosion*	*Crevice Corrosion*	*Erosion Corrosion*	*Cavitation*	*Stress Corrosion*
Bronze	*8*	*9*	*9*	*7*	*5*	
NiAlBrnze	*9*	*10*	*8*	*8*	*8*	*10*
Ni-Cu Alloy	*10*	*5*	*2*	*10*	*8*	*?*
Carbon	*3*	*3*			*2*	
Stainless	*10*	*4*	*3*	*10*	*7*	*8*
6Mo	*10*	*9*	*8*	*10*	*8*	*8*
Duplex	*10*	*5*	*4*	*10*	*8*	*9*
Superduplex	*10*	*9*	*8*	*10*	*8*	*9*
Ni Alloy 625	*10*	*13*	*12*		*13*	
Ni Alloy C22	*10*	*14*			*10*	
Titanium	*10*	*15*	*10*		*9*	

Figure 3: Comparative corrosion performance, part 1 (after Oldfield and Masters, 1996)

Arbitrary scale, higher is better	*Polluted Seawater*	*Corrosion Fatigue*	*Fouling Resistance*	*Galvanic*	*Wear & Galling*
Bronze			*10*	*5*	*10*
NiAlBrnze	*4*	*9*	*8*	*6*	*10*
Ni-Cu Alloy	*?*	*?*	*4*	*8*	*5*
Carbon				*1*	*8*
Stainless	*4*	*6*	*1*	*4/7*	*6*
6Mo	*9*	*6*	*1*	*9*	*5*
Duplex	*5*	*9*	*1*	*8*	*4*
Superduplex	*9*	*9*	*1*	*10*	*3*
Ni Alloy 625		*12*	*1*	*10*	*3*
Ni Alloy C22			*1*	*10*	*3*
Titanium			*1*	*9*	*2*

Figure 4: Comparative corrosion performance, part 2 (after Oldfield and Masters, 1996)

4 Relative Costs

As costs are so often the determining factor, a comparative review of valve materials would not be complete without some cost comparison. However, as markets set the value of the raw materials and as they have been particularly volatile in the recent past any comparison is likely to be out-of-date as soon as it is produced.

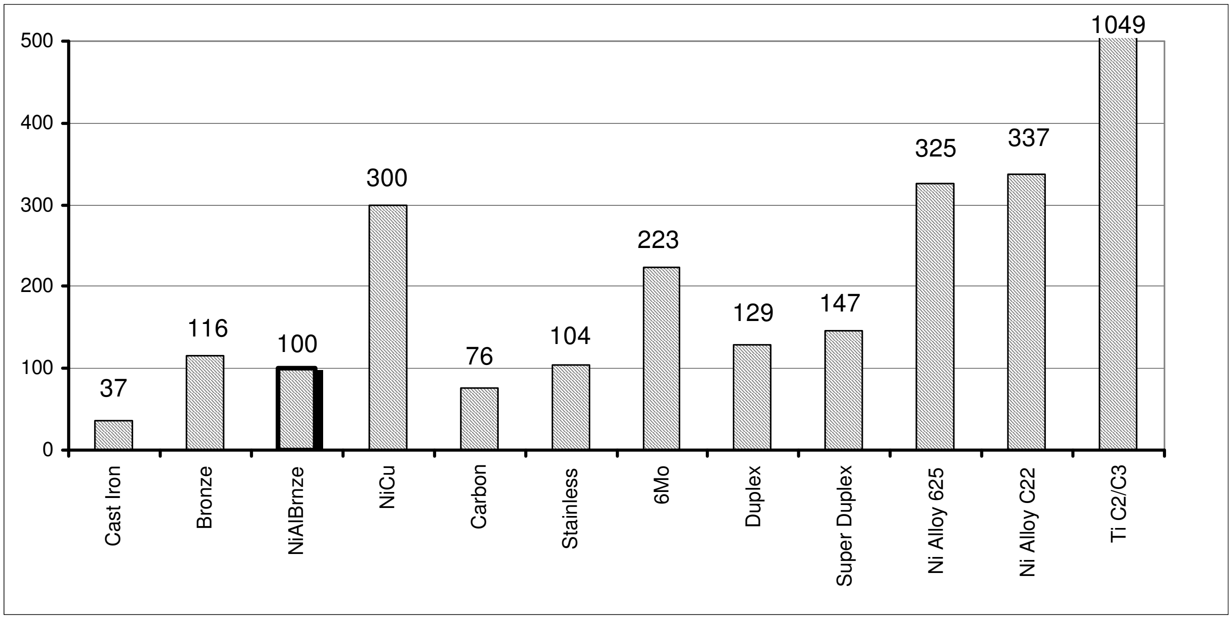

Figure 5: Relative cast costs per unit volume. (Index NAB=100)

Once again, the comparison is intended to be a guide. The values in *Figure 5* are a like-for-like comparison. The parameters are for a small quantity of a medium range (say 6" gate valve body) to the same design. Prices per kg have been adjusted by the relevant material density to ensure that the same volume is used in each case. As valves are made to standards with minimum wall sections this is a good approximation to reality, but does not allow for the detail design differences that would be necessary due to the different alloy characteristics. The data does not take into account the economies of scale that are undoubtedly available for large quantities in the more popular materials. An element of the quality testing that is commonly required has been included. These are typically charges per melt and so highly quantity dependent.

The density of bronze is greater than NAB, thus making it more expensive than NAB, although the material prices are similar per kg. The stainlesses are also denser than NAB with a similar effect. Machining prices have not been included, but in general terms this would increase the 6Mo, duplex, super duplex and Ni alloy prices relative to NAB.

A significant effect is the testing that is required to ensure the quality of the various materials. For example, for 6Mo, 22Cr and 25Cr, Shell ES/247 requires:

- Impact testing (not 6 Mo)
- Hardness testing
- Microstructural examination and ferrite phase balance (not 6 Mo)

– Pitting Corrosion testing (additionally, stress corrosion cracking for 25Cr if specified)

All this is in addition to dye penetrant testing and radiography which may be required on all materials. These are required to ensure that the casting process is fully controlled and does not produce an adverse structure.

NAB can be specified with heat treatment which can help ensure that the casting corrosion properties are maintained at optimum levels, but special testing is unusual.

The overall conclusion on costs is that stronger does not mean less if the design codes are adhered to and that the cost of quality assurance is also a significant element that must not be ignored.

5 Standards and NAB

The standards tend to regard NAB as bronze, treating it in the same way. As has been discussed earlier, there are significant differences in the mechanical properties of the two materials. The valve and flange standards do not recognise these differences. In general there are two main streams of flange and valve standards. These are shown below:

Origin	***Standards***	***Materials***	***Coverage***	***Pressures (CWP, bar)***
USA	ASME B16.24	B62, B61	Class 150,300 FF 150: 12” max 300: 8” max	Cl150=15.5 bar,300=34.5
		C95200	B16.5 R/F	Cl150=13.4 bar, 300=35.5
	EN1759-3:2003 (ISO 7005-3)	Various Cu alloy	Class 150,300 FF to DN900 (150) or DN600 (300)	Cl150=15.5 bar,300=34.5 Cl150, >DN350 14 bar Cl300, >DN250 20 bar
Europe	EN 1092-3:2003 (ISO 7005-3)	Various Cu alloy	PN6 – PN40 Flat or raised face DN500 (PN16) DN400 (PN40)	PN x = x bar, PN16 = 16 bar etc

The EN standards have a pressure temperature rating for NAB (CC333G), but apart from extending the high temperature performance beyond that of the bronzes, no recognition is made of the yield strength being over double that of the bronzes.

The American standard, B16.24 does have an aluminium bronze with dimensions to B16.5. This is still weaker than NAB (40%) and stronger than B62 (80%). However the dimensions in this instance require B16.5 dimensions with the raised face, explaining the reduction in the cold working pressure. The clause that allows bronze flange faces to be raised, provided that the extra dimension is added to the thickness appears to be inconsistent with these two ratings.

The European “PN” standards allow both raised and flat face dimensions and a full PN rating irrespective of the material. Due to the weak material and bending moments involved, extreme caution is required for all “bronze” materials with raised face flanges, particularly when bolting-up. Choice of gasket and assembly procedure using controlled bolt loads is critical. The author recommends that bronze flanges with raised faces are avoided wherever possible.

None of the standards recognise the high yield strength of NAB. However, the appendices of B16.34 and B16.5 do give a method for determining the pressure-temperature ratings. If this is used, a cold working pressure of NAB of 19 bar results (see *Appendix III)*. To calculate the pressures at higher temperatures, data on material properties is required. The rating, “SPT01” (Shipham pressure-temperature rating) is presented below in *Figure 6.*

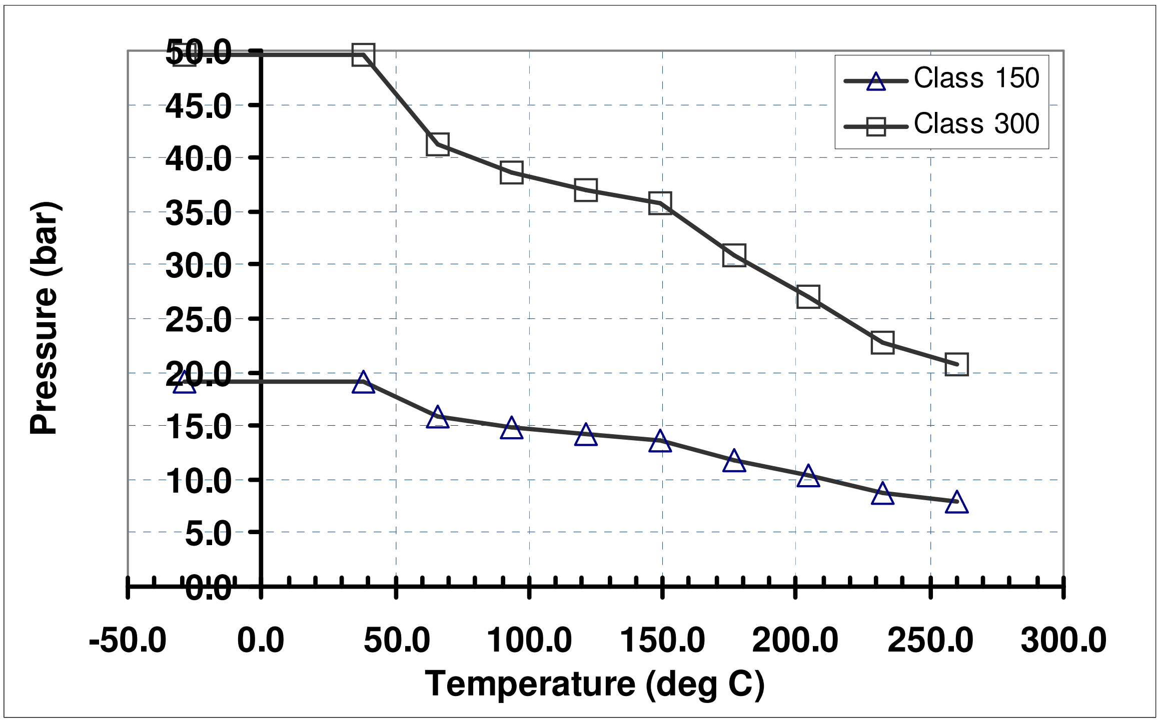

Figure 6: SPT01, pressure-temperature rating for NAB (UNS C95800 and similar)

This rating has been in use at Shipham for many years without any issues, is consistent with the B16.34 rules and enables the full potential of NAB to be safely maximised. It is conceivable that the high temperature ratings could be extended, but NAB is not generally used where this is a requirement and from experience has not found to be necessary

A similar approach is also required for other materials, particularly titanium. The data is more readily available as titanium is listed within ASME II, which NAB is not.

6 Conclusion

The advantages of NAB are significant. It is particularly suitable and useful for seawater service where its corrosion performance, particularly where its resistance to chloride pitting is excellent. The techniques of producing consistent castings of good quality are well understood and there is little need for the extensive non-destructive tests that are required in the case of 6Mo, duplex and super duplex steels.

Mechanically, NAB is comparable with other popular corrosion-resistant alloys, but to take full advantage of these properties, specially determined pressure-temperature ratings have to be used. The excellent galling and wear properties help ensure longevity and good performance of valves in NAB.

The limitations of NAB are that it should not be used in sulphide environments and account must be taken of its flow limitations. The rival materials of cast iron and steel need some form of protection to compete, and even then the quality and durability of this protection determine the life. Stainless steel suffers from severe crevice corrosion and pitting in seawater and the 6Mo, duplex and super duplex stainless steels have a temperature limitation of 20 ^{o}C for seawater service with a maximum chlorine content. The expense of the more exotic higher alloys becomes the critical factor, needing a special reason for justification.

While market prices vary, despite recent increases in the copper price, NAB remains a cost effective valve material for seawater service. However, compatibility with piping material is likely to be the factor that determines the valve material, the advantages suggest that NAB is capable of more than this.

Acknowledgement

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Author

The author is currently Technical Director of Shipham Valves, Hull, England. Address for correspondence is rons@shipham-valves.com

Appendix I: Alloys

Alloys used for comparative data in the charts and text are listed below:

Name	Std	Grade	UNS	Also known as
Cast Iron	Various			
Bronze	B62		C83600	Gunmetal, valve bronze, leaded bronze
NiAlBrnze	B148		C95800	NAB
Ni-Cu alloy	A494	M35-1	N24135	Monel ®
Carbon Steel	A216	WCB	J03002	
Stainless St.	A351	CF8M	J92600	316
6Mo	A351	CK-3MCuN	J93254	
Duplex	A890	4A	J92205	
Super Duplex	A744	CD-4MCu	J93370	
Ni Alloy 625	A494	CW-6MC	N26635	Inconel ® 625
Ni Alloy C22	A494	CX-2MW	N26022	Hastelloy ® C22
Ti C2	B367	C-2	R50400	
Ti C3	B367	C-3	R50550	

Further details on some of the above materials are in Appendix II.

Appendix II: Material Data

MATERIAL & SPECIFICATION		UNS	ELEMENTS											TENSILE (min)[2]	YIELD (min)[2]	Elongation[2]	Brinell [2]	Pressure Temp. Rating	Class 150 *Note: SPTxx are Shipham calculated values*			
GUNMETALS			Cu		Sn		Pb		Zn		Ni		E=120 kN/mm²	N/mm²		%		B16.34-2004	CWP (bar)	250 °C	max bar	at °C
													ρ=8.8 g/cm³									
B62		C83600	84.0	86.0	4.0	6.0	4.0	6.0	4.0	6.0	1.0		Cu min can be Cu+Ni	**205**	**95**	**20**		B16.24-2001	15.5	-	10.3	208
BS1400	LG2	obsolete	Bal		4.0	6.0	4.0	6.0	4.0	6.0	2.0			**200**	100	**13**						
EN1982	CC491K		83.0	87.0	4.0	6.0	4.0	6.0	4.0	6.0	2.0		Cu inc. Ni	**200**	90	**13**	60	EN1759-3:2003*	15.5	10.7	10.3	260
B61		C92200	86.0	90.0	5.5	6.5	1.0	2.0	3.0	5.0	1.0		Cu min can be Cu+Ni	**235**	**110**	**24**		B16.24-2001	15.5	10.6	9.6	288
BS1400	LG4	obsolete	Bal		6.0	8.0	2.5	3.5	1.5	3.0	2.0		Sn + .5Ni=7% to 8%	**250**	130	**16**						
EN1982	CC492K		85	89	6.0	8.0	2.5	3.5	1.5	3.0	2.0		Cu inc. Ni + as above	**230**	**130**	**14**	65	EN1759-3:2003*	15.5	10.7	10.3	260
NICKEL-ALUMINIUM BRONZES			Cu		Al		Fe		Ni		Mn	Zn	E=110 kN/mm²									
													ρ=7.6 g/cm³									
BS1400	AB2		Bal		8.8	10.0	4.0	5.5	4.0	5.5	3.0	0.5		**640**	**250**	**13**		see SPT01				
EN1982	CC333G		76.0	83.0	8.5	10.5	4.0	5.5	4.0	6.0	3.0	0.5		**600**	**250**	**13**	140	EN1759-3:2003*	15.5	12.7	10.3	350
B148		C95800	79.0		8.5	9.5	3.5	4.5	4.0	5.0	1.5			**585**	**240**	**15**		see SPT01				
Various	AB2/958/955/CC333G																	SPT01	19.0	8.2	7.9	260
Ni-Cu ALLOYS (MONEL®)			Ni		Cu		Si		Fe	Mn			E=179 kN/mm²									
													ρ=8.8 g/cm³									
BS3071	NA1		Rem		28.0	34.0		1.5	1.5	1.5				**430**	**170**	**20**						
BS3071	NA3		Rem		28.0	34.0	3.5	4.5	1.5	1.5				**630**			**250**					
A494	M35-1	N24135	Balance		26.0	33.0		1.3	3.5	1.5			(N04400)	**450**	**170**	**25**		(3.4)	15.9	12.1	3.7	475
A494	M35-2	N04020	Balance		26.0	33.0		2.0	3.5	1.5			(N04400)	**450**	**205**	**25**		(3.4)	15.9	12.1	3.7	475
STAINLESS STEELS																		* flat faced flanges only (similar materials)				
SUPER AUSTENITIC			Cr		Ni		Mo		Cu	N	Mn	Si	E=200 kN/mm²									
													ρ=8.0 g/cm³									
A351	CK-3MCuN	J93254	20.5	19.5	19.5	17.5	7.0	6.0	1.0	0.2	1.2	1.0	C 0.02 max	**550**	**260**	**35**	155	2.8	20.0	12.1	6.5	400
AVESTA	254 SMO	S31254	20.5	19.5	18.5	17.5	6.5	6.0	1.0	0.2			C 0.02 max	650	300	35	210	(2.8)	20.0	12.1	6.5	400
A743	CN-3MN	(N08367)	20.0	22.0	25.5	23.5	6	7.0	0.75	0.2	2	1	C 0.03 max	**550**	**260**	**35**		3.12	17.8	12.1	5.5	425
A743	CN-7M	N08007	19.0	22.0	27.5	30.5	2	3.0	3.5	-	1.5	1.5	C 0.07 max, sim to N08020	**425**	**170**	**35**		3.17	15.9	10.4	9.3	325
B649	(forging)	N08904	19.0	23.0	23	28	4	5.0	1.5	-	2		C 0.02 max	500	220	35	180	3.11	19.7	12.1	7.4	375

[2] Figures in bold are mandatory in the standard.

MATERIAL & SPECIFICATION		UNS	ELEMENTS											TENSILE (N/mm^2)	YIELD (N/mm^2)	Elongation (%)	Brinell	Pressure Temp. Rating (B16.34-2004)	Class 150 *Note: SPTxx are Shipham calculated values* CWP (bar)	250 °C	max bar	at °C
DUPLEX			Cr		Ni		Mo		Cu	N	Mn	Si	E=200 kN/mm^2 ρ=7.8 g/cm^3									
A890	4A	J92205	21.0	23.5	4.5	6.5	2.5	3.5	1.0	0.3	1.5	1.0	C 0.03 max	**620**	**415**	**25**		(2.8)	20.0	12.1	9.6	315
A351	CD3M-WCuN	J93380	24.0	26.0	6.5	8.5	3.0	4.0	1.0	0.3	1.0	1.0	W 1.0,C.03, UNS S32760	**700**	**450**	**25**		(2.8)	20.0	12.1	9.6	315
A744	CD-4MCu	J93370	24.5	26.5	4.8	6.0	1.8	2.3	3.0	-	2.0	1.0	Ferralium,UNS S32550	**690**	**485**	**16**		2.8	20.0	12.1	9.6	315
A789	SAF 2507	S32750	24.0	26.0	6.0	8.0	3.0	5.0	0.5	0.3	1.2	-						2.8	20.0	12.1	9.6	315
NICKEL ALLOYS (1) (Inconel ®, Incoloy ®)													E=196, 206 kN/mm^2 ρ=8.1, 8.4 g/cm^3									
B424	Incoloy	N08825	19.5	23.5	38.0	46.0	2.5	3.5	3.0	-	1.0	-	Fe bal,Ti 1.0 max					3.8	20.0	12.1	1.4	538
A494	CU5MCuC		19.5	23.5	38.0	44.0	2.5	3.5	3.5	-	1.0	1.0	Fe bal,Ti 1.2 max	**520**	**240**	**20**		(3.8)	20.0	12.1	1.4	538
A494	CW-6MC	N26635	20.0	23.0	bal		8.0	10.0	-	-	1.0	1.0	Fe 5 max, UNS N06625	**485**	**275**	**25**		(3.8)	20.0	12.1	1.4	538
NICKEL ALLOYS (2) (Hastelloys ®)													E=217, 205 kN/mm^2 ρ=9.2, 8.7 g/cm^3									
A494	N-7M	J30007	0.0	1.0	bal		30.0	33.0	-	-	1.0	1.0	UNS N10665,B2	**525**	**275**	**20**		(3.7)	20.0	12.1	5.5	425
A494	CX-2MW	N26022	22.0	22.5	bal		12.5	14.5	-	-	1.0	0.8	UNS N06022,C22	**550**	**280**	**30**		(3.8)	20.0	12.1	1.4	538
TITANIUM			Ti		Al		Va		O	Fe	C	N	E=110 kN/mm^2 ρ=4.4 g/cm^3									
B367	C-2	R50400	Bal		-		-		0.4	0.2	0.1	0.05	R52250	345	275	15		SPT02	16.2	8	7.7	260
B367	C-3	R50550	Bal		-		-		0.4	0.25	0.1	0.05	R52250	450	380	12		SPT04	20.0	8.7	8.4	260
B367	C-5	R56401	Bal		5.5	6.8	3.5	4.5	0.25	0.4	0.1	0.05		895	825	6		(not rec)				
ZIRCONIUM			Zr		Nb		Fe + Cr		Hf				E=99 kN/mm^2 ρ=6.6 g/cm^3									
B752	702C	R60702	Bal		-	-	0.3		4.5					**380**	**276**	**12**	**210**	SPT03	17.8	8.8	5.9	370
B752	705C	R60705	Bal		2	3	0.3		4.5					**552**	**379**	**12**	**235**					

Appendix III:

Pressure-temperature calculation

Reference ASME B16.34-2004 Appendix B

For the cold working pressure of NAB to ASTM B148 UNS C95800

Tensile strength, 85 000 psi
Yield strength, 35 000 psi

S_1, selected stress is the lower of:

(1) 60% x yield = 60% x 35 000 psi = 21 000 psi
(2) 1.25 x 25% x tensile = 1.25 x 25% x 85 000 psi = 26 560 psi

Therefore S_1= 21 000 psi

For class 150, p_r=115 and C1=1

$p_{st} = C_1 S_1 \, p_r / 8750$

p_{st} = 1 x 21 000 x 115 / 8 750 = <u>276 psi, 19 bar</u>

Appendix IV

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Several other material standards have been referred to in passing: identification by the standard number used should suffice.