Nickel-Aluminium Bronze for Seawater:
Flattered by Comparison

By J R C Strang, Shipham Valves

Keywords:

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

Abstract

In current cash strapped times, cost effectiveness is more important than it has been for a long time. The temptation of cheap materials can seem difficult to resist, but investors and operators are keenly aware of through-life costs and most are unwilling to sacrifice reliable long-term performance for a one-off gain. Clearly a compromise is called for between the expense of an ultimate solution and one that cannot be relied upon for more than a few months.

Nickel-aluminium bronze (NAB) represents just such an alternative: in terms of cost it sits between the exotic and expensive alloys of super duplex, nickel alloys and titanium and the lower cost options of cast iron or carbon steel at the other. The aim of this paper is to show that the NAB solution is cost effective, providing a long service life without compromising on the performance or by being penalised on cost.

Nickel-aluminium bronze is no newcomer, has been used extensively for seawater service for many years and is widely recognised to be an excellent solution. By comparing the properties and costs with a range of material options including the copper alloys, the duplex stainless steels, nickel alloys and titanium, this paper will demonstrate that NAB can be a cost effective choice. The review draws 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 consequences of the most common NAB alloy not featuring in the popular flange and valve standards will be discussed. Suggestions of how to overcome this will also be made with reference to a specially developed NAB pressure-temperature rating which maximises the potential of NAB as well as recognising its limitations, enabling an economic and safe design.

The fact that NAB is:

- *cost effective (cheaper than the exotic alternatives);*
- *long lasting (comparable in performance on general corrosion, pitting and cavitation to superduplex alloys and significantly better than the standard alloys), and*
- *a good valve material (does not gall, has excellent anti-fouling properties and is a good thermal conductor),*

makes it an excellent choice for valves in seawater service.

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

About the Author

J R C (Ron) Strang (Eur. Ing,. BSc, CEng, FIMechE, MBA), graduated as a Mechanical Engineer from Aston University in 1981 and from Hull University with an MBA in 2007. He has worked in the design and development of valves, initially with Serck Audco Valves, and then Orseal Valves. For the last 16 years he has been employed as Technical Director at Shipham Valves in Hull. Shipham manufactures extensively in nickel-aluminium bronze, as did Orseal Valves.

1 Introduction

It is essential to be clear that we are discussing nickel-aluminium bronze (NAB), not bronze and not aluminium bronze, although NAB is frequently referred to as aluminium bronze. As will be shown, significant differences exist.

There are several myths associated with this material. First, it is weak. Consider Figure 1:

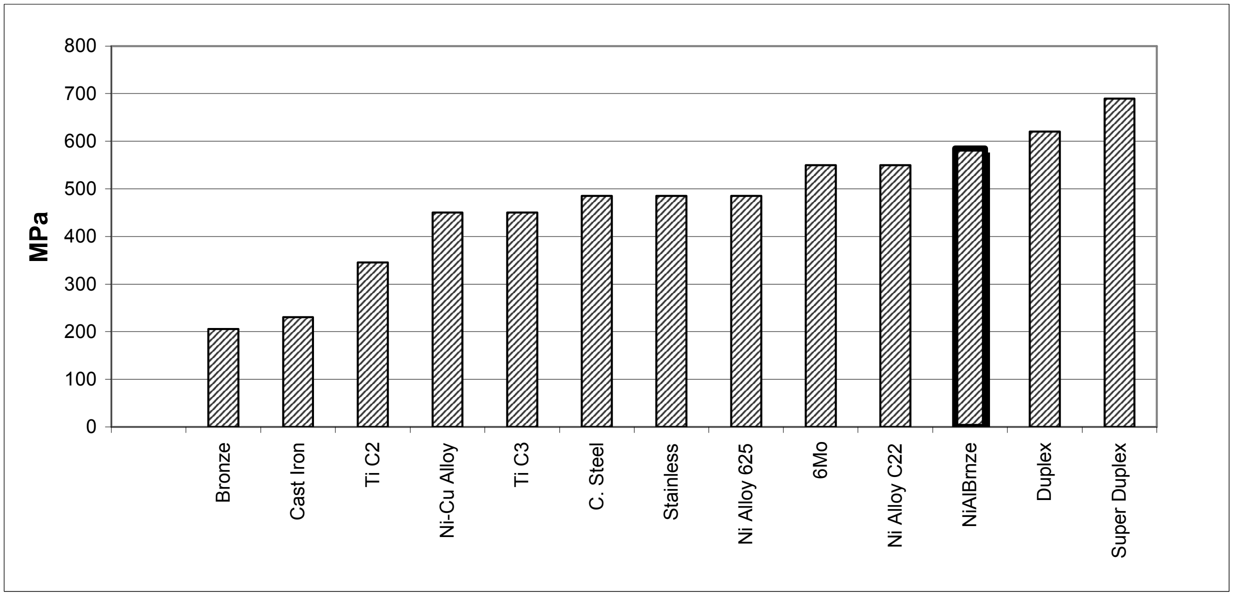

Figure 1: Tensile Strengths of Cast Materials

While tensile strength does not give the full picture, the material cannot be considered weak.

Second, it is expensive. Again some facts – see Figure 2. The reality is somewhat different to the common belief.

There are other myths too such as “It is not available”, “It is difficult to cast” and “Pressure-temperature ratings are not good enough”.

In the times of the credit crunch, cost effectiveness is more important than ever. Choosing the right material and balancing initial investment with a good through-life cost is important. The sacrifice of reliable long-term performance for a one-off gain on purchase cost is clearly not an economic decision. A compromise between the expense of the ultimate solution and one that cannot be relied upon for more than a few months is required. This paper shows that this is a role that NAB as a cast valve material for seawater service can fulfil.

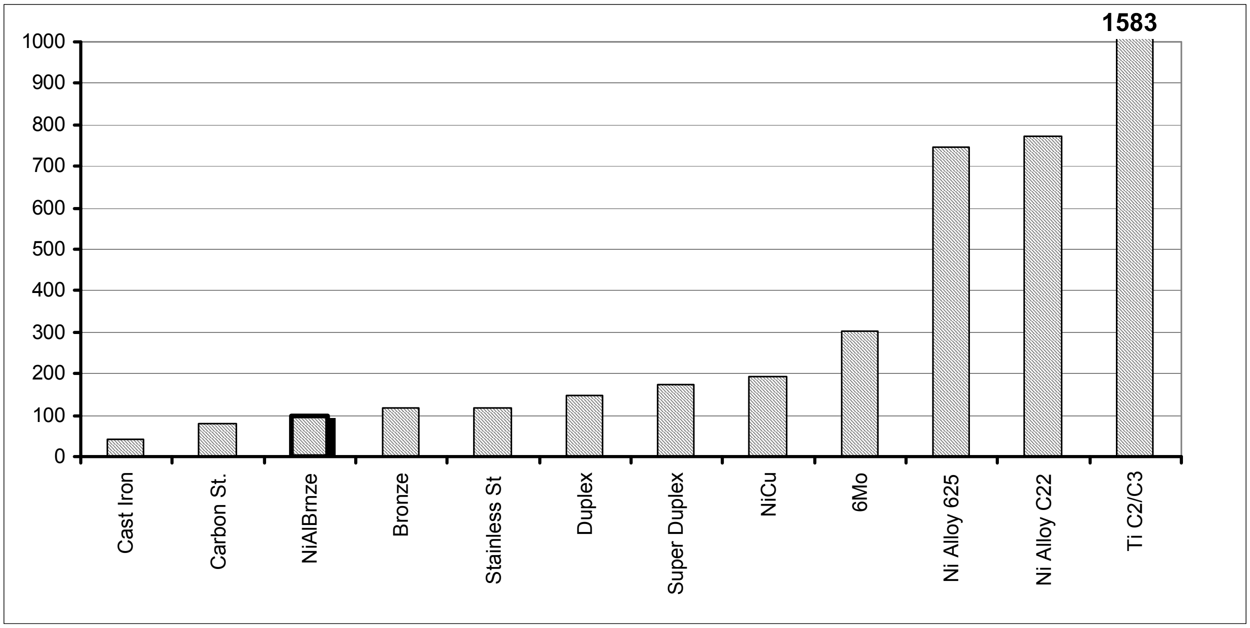

Figure 2: Relative Cast Costs/ Unit Volume (NAB-100)

2 What is Nickel-Aluminium Bronze?

Nickel-aluminium bronze is not bronze. The only similarity is that they are both copper alloys. Bronze, discovered in the 4th millennium BC, the Bronze Age, is the combination of copper and tin. The fact that aluminium bronze shares its name with this material must be part of the reason for some of the myths.

Aluminium bronze and NAB are relatively recent innovations. They required some casting sophistication that became available in 1913 when Durville perfected his tilting ladle process to make aluminium bronze billets. This “Durville Process” overcame the problem of shrinkage defects and oxide inclusions inherent to the alloys, partially due to the narrow freezing range.

Charles H Meigh developed this process and investigations by metallurgists ensured the development of the alloys. Its common commercial usage grew, driven by the requirement for ships’ propellers suitable for increasing speeds. It has become the most popular material for this use, because “… nickel-aluminium bronze (NAB) is twice as resistant to corrosion fatigue as manganese bronze and stainless steel …” (Meigh, 2000, xxix). Growth in the oil industry and the need, initially for seawater fire pumps, has also spread the use of NAB. Navies too have used NAB extensively due to its strength and weldability. The loss of the US nuclear submarine Thresher in 1963, thought to be due to a bronze casting failure, hastened the uptake of NAB for use on submarines. (Meigh, 2000)

The choice of valve material is frequently determined by the choice of pipe material. Therefore as copper-nickel pipe became well established, so did the use of NAB valves. However, for reasons of weight, strength and velocity limitations (erosion damage in the Cu-Ni pipe above 3.5 m/s) newer materials were considered: a 20” CuNi diameter pipe could be replaced by a 14” 254 SMO material. (Gallager, Mallpas & Shone, 1986). However, experience of the newer materials (duplex, super duplex, titanium) showed that there are temperature, cost and quality limitations. More recently, NAB valves are being used with GRE pipe.

The most popular alloy for valve applications is with 8% - 11% of aluminium and the addition of iron and nickel to give a high strength and good corrosion resistance. This is a duplex alloy and is available in both cast and wrought forms. 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, 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.

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

No material is perfect and it is only when comparisons are made that performance appropriate for the particular service can be properly evaluated. A range of materials often used for seawater has been selected and NAB will be compared with these alloys in terms of cost, corrosion and mechanical performance. The alloys chosen are listed in Appendix I, together with their specifications.

3 Relative costs

Cost is often the most important factor when choosing a material – sometimes it seems to be the only one. It is not a simple equation when all the factors beyond initial investment are considered. The material cost is not stable: volatile material indices and exchange rates ensure that the most cost effective solution one day is not necessarily still the right choice the next as Figure 3 shows.

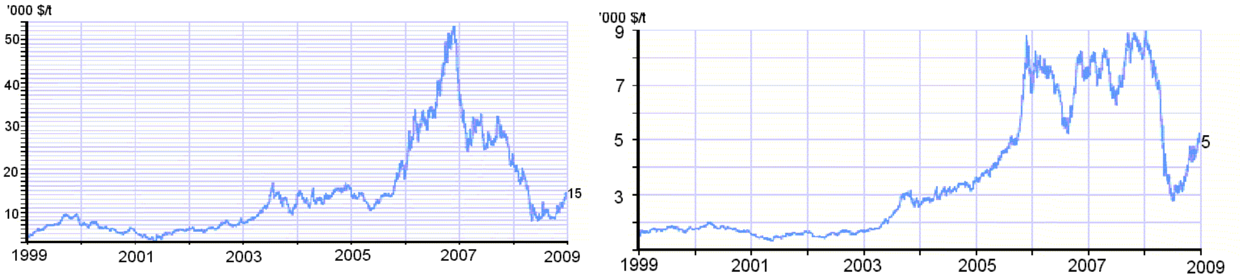

Figure 3: LME Nickel (left) and Copper (right) prices for the last 10 years

An approximate comparison of finished casting prices is shown in Figure 4. These are based on a small quantity of a medium range (say a 6” gate valve body) to the same design. The relevant material density has been used to adjust the prices per kg to ensure that the same volume is used in each case. This is a good approximation to reality as valves are made to standards with minimum wall sections. This however does not allow for the detail design differences necessary due to the different alloy characteristics. The figures do not take into account the economies of scale that would be available for large quantities. An element of the quality and non-destructive examination (NDE) that is commonly required has been included. These are typically charges per melt and so highly quantity dependent.

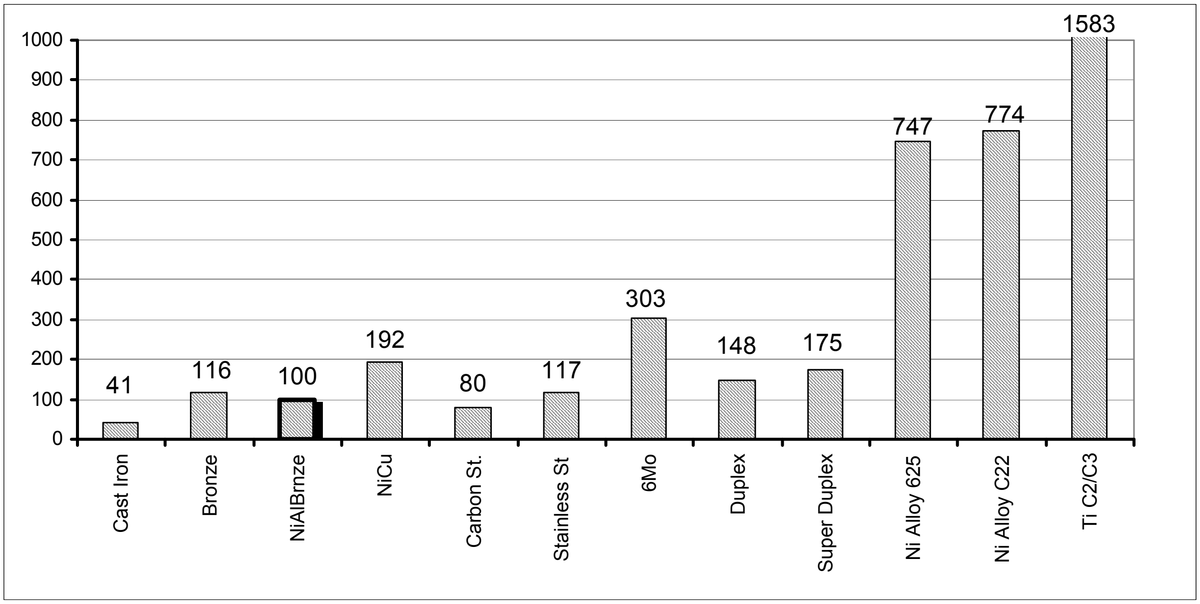

Figure 4: Relative cast costs per unit volume. (Index NAB=100)

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

The NDE and testing required to ensure the quality of the various materials is significant. For example, Shell DEP 30.10.02.35 (formerly 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)

for 6Mo, 22Cr and 25Cr materials. 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 a temper anneal heat treatment which helps ensure a favourable microstructure and that the casting corrosion properties are maintained at optimum levels (Chen et al, 2007) to improve corrosion resistance. However, Michels & Kain (2007) show that the correct chemical content is more significant. Special testing for NAB is unusual.

NAB is clearly competitive on costs, particularly if the cost of quality assurance is considered.

4 Corrosion comparison

Corrosion is a complex topic with many variables, including the precise chemical constituents of the metal concerned, its microstructure and its heat treatment. This is further complicated by the infinite variety of service conditions. The medium itself is only one element, the environment, pressure, temperature and flow-rate are others that can have a significant effect. Even limiting consideration to seawater is not straightforward; 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 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 you are searching for is not available directly. 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. While the details given in the following paragraphs are believed to be generally correct, the specific details in any particular situation should always be considered.

4.1 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.

4.2 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, affecting stainless and duplexes but not NAB. For materials that are affected, there are tests that give a critical pitting temperature (CPT) and there is a calculation to assess the 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, indicates susceptibility to pitting). These tools give an indication of pit initiation, rather than pit propagation. Worst affected are the steels and 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 for duplexes to avoid pitting, including coating and cathodic protection as well as removal of oxygen. (Smith, Celant & Pourbaix, 2000; HSE Safety Notice 7/2007, Norsok M-001).

NAB is not considered to be affected by chloride pitting, attack in crevices is minimal and does not produce pitting or serious roughing of the surface. It is also reported to show no tendency to chloride stress corrosion cracking. (Oldfield and Masters, 1996; Horwath, 2002)

4.3 Velocity effects

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

Fouling occurs when marine organisms attach themselves to the material. Due to differential aeration effects, this sets up a corrosion cell. Copper alloys have an excellent fouling resistance due to the formation of a film of cuprous oxide corrosion product on the surface which is inhospitable to marine organisms (Efird, 1975). 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 have 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 to 5 m/s is frequently quoted as the limit for NAB with a recommendation of 10 m/s as an intermittent maximum, (Norsok M-001, Wharton et al, 2005) whereas 23 m/s is a guideline for the peripheral velocity of pumps and propellers (Tuthill, 1987).

4.4 Temperature

In general, temperature will accelerate the rate of any chemical reaction, so corrosion processes take place more quickly. However, raised temperatures also lead 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 or 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. Additionally, NAB does not undergo a brittle transition at low temperatures and can be used for cryogenic temperatures. However, bronze tends to be preferred in this instance due to its better oxygen compatibility.

4.5 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.

4.6 Other corrosive conditions

In common with most materials considered here, NAB experiences problems in the presence of hydrogen sulphide. Therefore it should not be used in polluted seawater conditions and precautions are advised such as passivation in clean seawater as well as using a suitable range of flow rates. (Guyader et al., 2007; Blake, 2001; Oldfield & Masters, 1996). Precautions are also

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[1] *But 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)*

advised for duplex materials (Smith et al, 2000; Norsok M-001, Aramco SAES-L-105).

In general, NAB is good in acidic environments, but as strongly alkaline environments remove the protective film, corrosion rates in this case can be high.

4.7 Corrosion summary

Building on earlier work (Oldfield and Masters, 1996), the tables in Figs 5a and 5b are a summary of the relative corrosion of the materials considered. The scale is arbitrary and 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). Columns for wear and galling performance have 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 5a: 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 5b: Comparative corrosion performance, part 2 (after Oldfield and Masters, 1996)

5 Mechanical properties

Returning to the myth of NAB being weak: the tensile and yield strengths are shown graphically in Figure 6.

This illustrates several points clearly. First, the difference between “bronze” and NAB is significant and shows the association with 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).

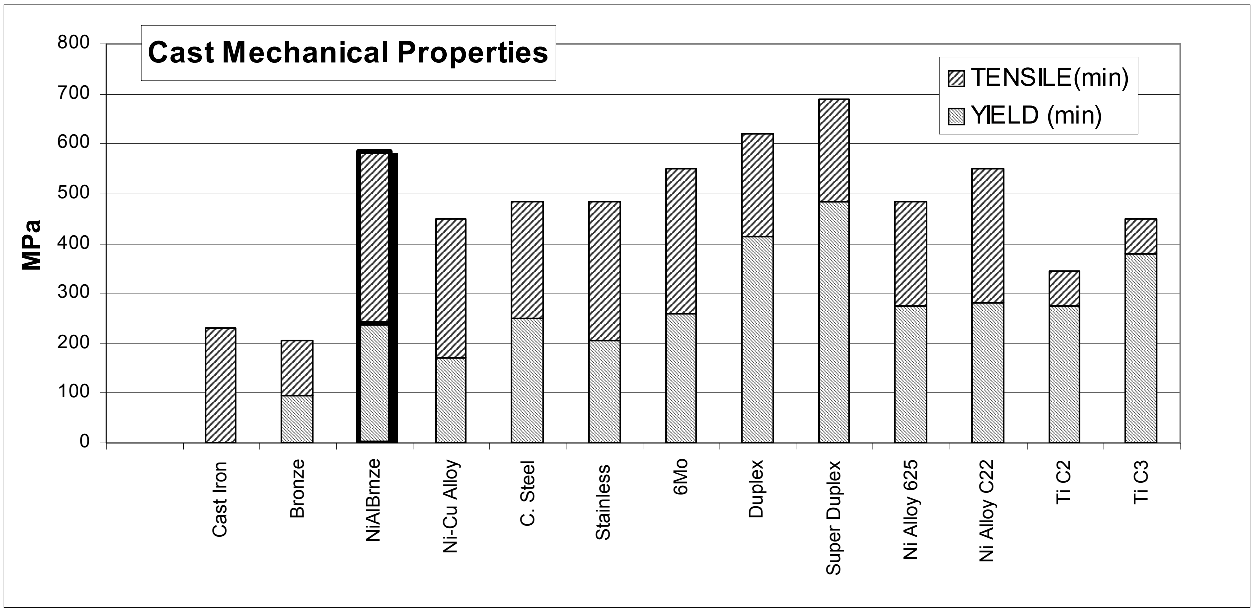

Figure 6: Mechanical Properties of Selected Cast Alloys

Second, perhaps more surprisingly, NAB’s mechanical properties are better than those of Ni-Cu alloy (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. Additionally, the common carbon and stainless steels materials do not differ significantly as far as these properties are concerned. The duplex and super-duplex materials are the only ones to significantly exceed the mechanical properties of NAB. Even the commonly used grades of titanium have an inferior performance to NAB.

Although the ductility of NAB is not as high as most of the materials compared, it matches titanium and, with a 15% elongation, cannot be considered brittle.

For valves, the mechanical properties by themselves are not a determining factor. Variety is reduced and standardisation is greatly assisted by adopting a philosophy of a standard set of dimensions with a pressure-temperature rating dependent on the material. This is based on material mechanical properties taking account of the performance at varying temperatures. So when comparing materials, it is the pressure temperature rating that should be compared.

Figure 7 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. Additionally, in the absence of appropriate standards, the NAB and titanium ratings have been specially calculated.

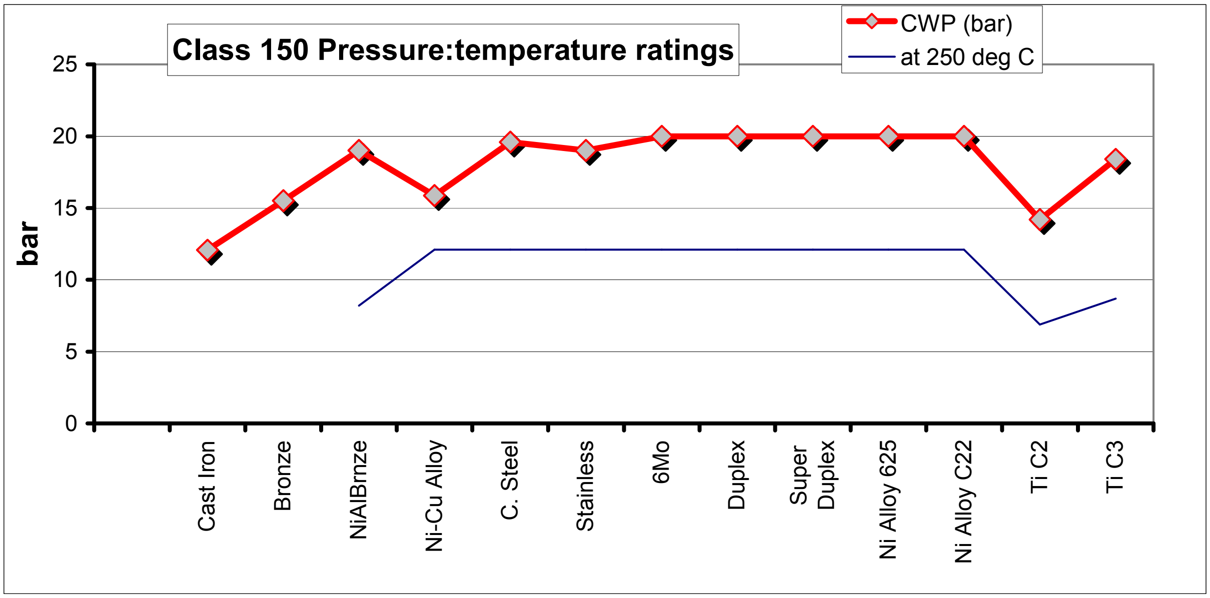

Figure 7: Comparative pressure - temperature ratings

The differences across all materials are now not as pronounced. The explanation for this is that an upper limit on the pressure is imposed in order to limit deflection. The materials affected by this ceiling figure are 6Mo, the duplexes and Ni alloys where the maximum pressure is reduced to 20 bar.

For comparison, the rating at 250 ^{o}C is included. The NAB and titanium values are lower than most of the other materials. The maximum temperature and pressure for each material is given in Appendix II. The ceiling values at higher pressures further reduce the differences between materials.

So NAB is not weak: it compares well enough to compete seriously with its rivals. There is a high temperature limitation but this is not generally an issue for seawater service.

6 Standards and NAB

The association with bronze becomes damaging once standards are considered: they tend to regard NAB as a bronze. Given that the NAB yield strength is over twice that of bronze, this is a very cautious approach and does not make use of the full NAB capabilities. The copper alloy standards fall into two groups with different approaches. 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 alloys	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

Summarising the above approaches, the US (ASME) standards are for bronze and rate class 150 at 15.5 bar. The European (EN) standards rate the flanges at the nominal pressure and apply this CWP rating to all copper alloys.

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.

ASME B16.24 does have an aluminium bronze (C95200) with dimensions to B16.5. This material is 40% weaker than NAB and 80% stronger than B62. However, the dimensions in this instance are to B16.5 with a raised face; this explains the reduction in the cold working pressure. The clause that allows bronze raised face flanges, provided that the extra dimension is added to the thickness, appears to be inconsistent with these two ratings.

The EN PN-rated standards allow both raised and flat face flanges 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. The choice of gasket will be important as will using an assembly procedure with carefully controlled bolt load. The safety factors inherent in a raised face flange with a bronze material will be minimal. The author therefore recommends that bronze flanges with raised faces are avoided wherever possible.

The high yield strength of NAB is not recognised by any of the standards. This can be addressed by a specially calculated pressure-temperature rating. The appendices of B16.34 and B16.5 give a method for this calculation. If this is used, the NAB cold working pressure is 19 bar (see Appendix III). For pressures at higher temperatures, data on material properties is required. The rating, "SPT01" (Shipham pressure-temperature rating) is presented below in Figure 8.

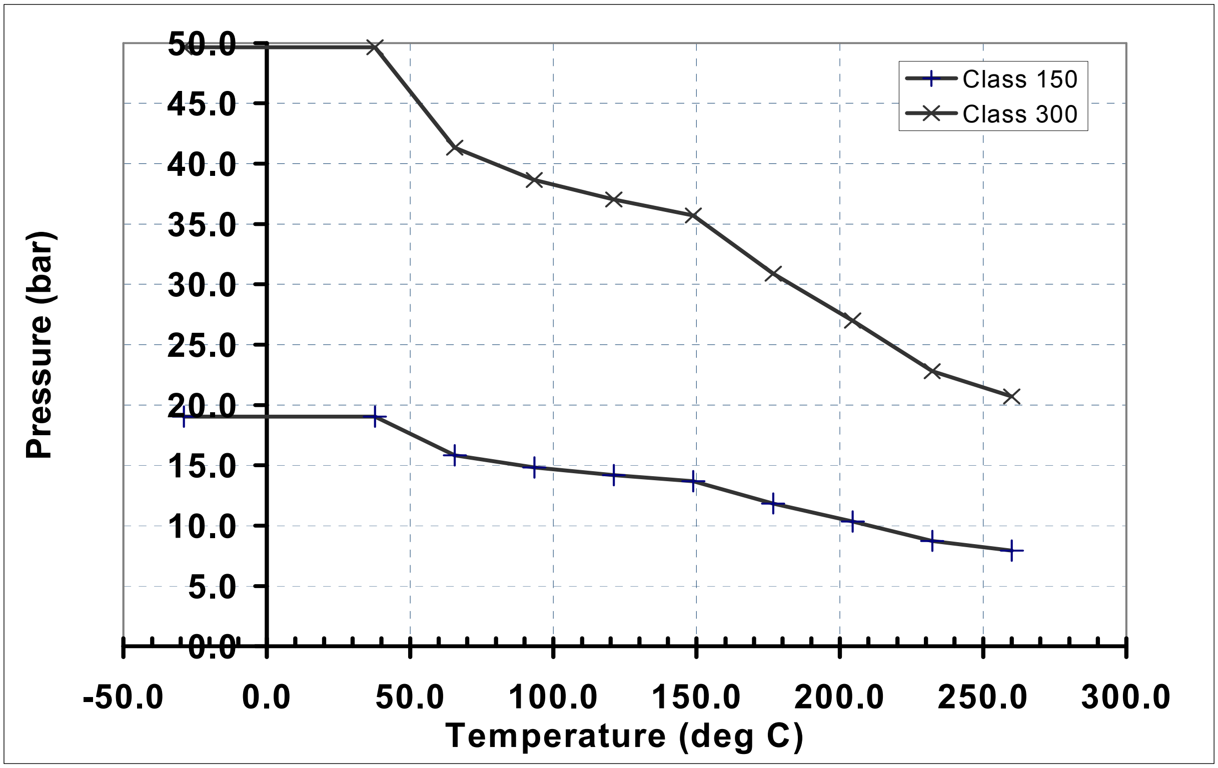

Figure 8: SPT01, pressure-temperature rating for NAB (UNS C95800 and similar)

This rating has been in use at Shipham for many years without any issues. It is consistent with the B16.34 rules and enables the full potential of NAB to be safely maximised with full use of raised face flanges. A cautious approach to the higher temperature ratings has been taken making an allowance for potential creep at above 150 ^{0}C. These elevated temperature ratings could be raised, but as it is unusual to use NAB at raised temperatures, this has not found to be necessary.

A similar approach is also required for other materials not listed in B16.5 and B16.10, particularly titanium. The data is more readily available as titanium is listed within ASME II, which NAB (C95800) is not.

7 Conclusions

Ultimately, compatibility with the selected piping material is likely to be the factor that determines the valve material choice: this limits NAB valves to CuNi or GRP / GRE pipe. Even here, taking full advantage of the excellent mechanical properties by using specially determined pressure-temperature ratings ensures that the optimum valve solution is used.

All the alloys considered have drawbacks. In common with many of the materials, NAB should not be used in sulphide environments and account must be taken of its flow limitations. 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 maximum chlorine content. The expense of the more exotic higher alloys ensures that a special reason is required for their justification.

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.

Nickel-aluminium bronze is a cost-effective material that has a corrosion performance significantly better than the low-grade carbon and stainless steels and without the significant price penalties of the higher alloys. 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.

Once nickel-aluminium bronze is fully understood and the common myths exposed, it can be seen that its advantages are significant. This is particularly the case when seawater is considered and compared to other potential materials for this service. Indeed NAB is flattered by comparison.

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	CK3MCuN	J93254	
Duplex	A890	4A / CD3MN	J92205	
Super Duplex	A744	1A / CD4MCu	J93370	
Ni Alloy 625	A494	CW6MC	N26625	Inconel ® 625
Ni Alloy C22	A494	CX2MW	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 GPa	MPa		%		B16.34-2004	CWP (bar)	250 °C	max bar	at °C
													ρ=8.8 g/cm^3									
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 GPa									
													ρ=7.6 g/cm^3									
BS1400	AB2	obsolete	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
B148-97		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 GPa									
													ρ=8.8 g/cm^3									
BS3071	NA1	obsolete	Rem		28.0	34.0		1.5	1.5	1.5				**430**	**170**	**20**						
BS3071	NA3	obsolete	Rem		28.0	34.0	3.5	4.5	1.5	1.5				**630**			**250**					
A494-08	M35-1	N24135	Balance		26.0	33.0		1.25	3.5	1.5			(N04400)	**450**	**170**	**25**		3.4	15.9	12.1	3.7	475
A494-08	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 GPa									
													ρ=8.0 g/cm^3									
A743/351	CK3MCuN	J93254	19.5	20.5	17.5	19.5	6.0	7.0	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
A743-06	CN3MN	J94651	20.0	22.0	23.5	25.5	6.0	7.0	0.75	0.22	2	1	C 0.03 max	**550**	**260**	**35**		3.12	17.8	12.1	5.5	425
A743-06	CN7M	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

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

MATERIAL & SPECIFICATION		**UNS**	**ELEMENTS**											TENSILE	YIELD	Elongation	Brinell	Pressure Temp. Rating	Class 150 *Note: SPTxx are Shipham calculated values*			
														MPa		%		B16.34-2004	CWP (bar)	250 °C	max bar	at °C
DUPLEX			**Cr**		**Ni**		**Mo**		**Cu**	**N**	**Mn**	**Si**	E=200 GPa									
													ρ=7.8 g/cm^3									
A890/995	4A /CD3MN	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
A351/995	6A/CD3M-WCuN	J93380	24.0	26.0	6.5	8.5	3.0	4.0	0.5-1.0	0.2-0.3	1.0	1.0	W 1.0,C.03, UNS S32760	**690**	**450**	**25**		2.8	20.0	12.1	9.6	315
A744/890/351	1A/CD4MCu	J93370	24.5	26.5	4.75	6.0	1.75	2.25	2.75-3.25	-	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 GPa									
													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
A494-08	CU5MCuC	N08826	19.5	23.5	38.0	44.0	2.5	3.5	1.5-3.5	-	1.0	1.0	Fe bal,Ti 1.2 max	**520**	**240**	**20**		(3.8)	20.0	12.1	1.4	538
A494-08	CW6MC	N26625	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 GPa									
													ρ=9.2, 8.7 g/cm^3									
A494-08	N7M	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
A494-08	CX2MW	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 GPa									
													ρ=4.4 g/cm^3	Tensile requirements to supplement S6								
B367-08b	C-2	R50400	Bal		-		-		0.4	0.2	0.1	0.05	R52250	345	275	15		SPT02/3	14.2	6.9	6.7	260
B367-08b	C-3	R50550	Bal		-		-		0.4	0.25	0.1	0.05	R52250	450	380	12		SPT04/2	18.4	8.7	8.4	260
B367-08b	C-5	R56401	Bal		5.5	6.75	3.5	4.5	0.25	0.4	0.1	0.05		895	825	6		(see SPT04)				
ZIRCONIUM			**Zr**		**Nb**		**Fe + Cr**		**Hf**				E=99 GPa									
													ρ=6.6 g/cm^3									
B752-06	702C	R60702	Bal		-	-	0.3		4.5					**380**	**276**	**12**	**210**	SPT03/3	15.6	6.5	4.3	371
B752-06	705C	R60705	Bal		2	3	0.3		4.5					**483**	**345**	**12**	**235**	SPT05/1	19.8	10.3	7.6	371

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.