EFFECTIVE DESIGN USING TITANIUM

by David K. Peacock, CEng., M.I.Corr., F.I.M.*

Summary

The effective and successful use of titanium requires the recognition, understanding and correct application of the unique combination of useful physical, mechanical and corrosion resistant properties which titanium possesses. These properties are considered in turn, and guidance is given to design for end use and fabrication, using available products and cost effective methods.

Introduction

This paper identifies and details the principal factors to be considered in successful and effective design using titanium. These are, mechanical and thermal performance, corrosion resistance, practical aspects of fabrication and installation, product availability and price.

Titanium is light and strong and has a family of alloys offering forms and properties appropriate to a wide variety of applications and working environments. Choice of the correct alloy, product form and manufacturing route provide the means of achieving the lowest cost design. Successful use of the metal in heat exchangers and condensers has confirmed the parameters for effective heat transfer.

Titanium and its alloys are resistant to corrosion in a wide range of aggressive conditions. Outstanding resistance to seawater, brines, brackish waters and chlorides is of particular importance. Product availability is good in all of the industrially familiar semi-finished products and components. Fabrication techniques for machining, forming , welding and other processes are well understood, and whilst different in some respects to those used for other metals, are not to any significant extent more costly, nor more difficult to apply successfully.

The final section of this paper gives some background information on availability and price, and the correct approach to costing titanium in its role as an industrial metal of ever increasing importance.

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The Mechanical Properties of Titanium and its Alloys

The range of grades and alloys of titanium available to the designer makes possible the selection of a combination of properties appropriate both to fabrication and end use. A convenient and widely used system for identification of the various grades of commercially pure titanium and titanium alloys used for engineering and corrosion resisting applications is provided by ASTM:-

Grades 1,2,3,4 are commercially pure titanium, used primarily for corrosion resistance. Strength and hardness increase, and ductility reduces with grade number. Grade 2 is the most widely used specification in all product forms. Grade 1 is specified when superior formability is required. Grades 3 and 4 are used where higher levels of strength are necessary.

Grades 7, 11 and 12 are alloys possessing superior corrosion resistance in particular to reducing acid chlorides. The mechanical properties of grades 7 and 11 are identical to those of Grades 2 and 1 respectively. Grade 12 is stronger and retains useful levels of strength up to 300°C.

Grades 5 and 9 are alloys with good corrosion resistance and medium levels of strength. They are frequently limited in use to specific products.

Beta-C is included as an important high strength corrosion resistant alloy for sea water application, which has not yet received an ASTM grading.

The range of ASTM specifications cover all the forms supplied in titanium and its alloys:-

ASTM B 265 - Strip Sheet and Plate

ASTM B 337 - Seamless and Welded Pipe

ASTM B 338 - Seamless and Welded Tube

ASTM B 348 - Bars and Billets

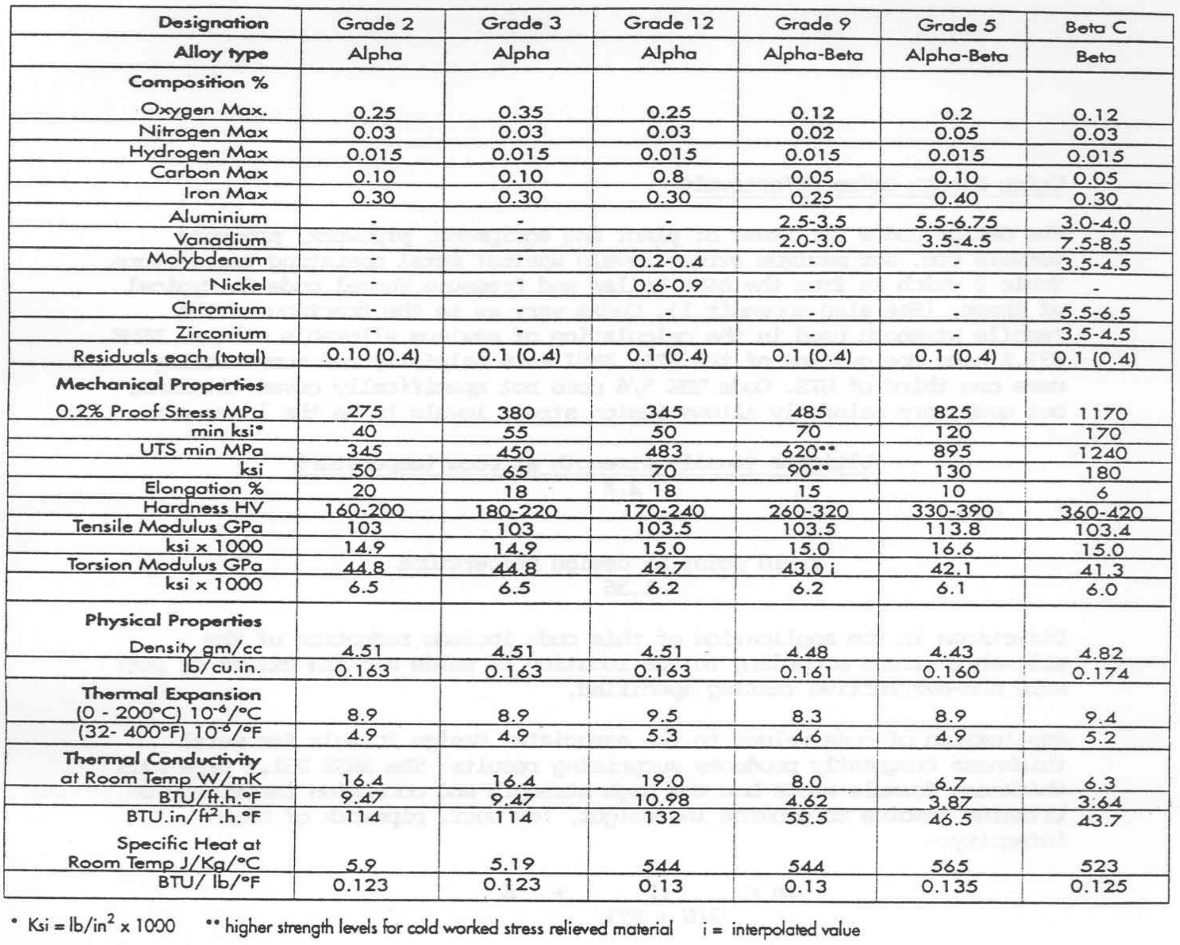
ASTM B 363 - Seamless and Welded Fittings

ASTM B 367 – Castings

ASTM B 381 - Forgings

Welding consumables are covered by AWS Specification A5.16.
A summary of key properties appears in Table 1, over. (1)

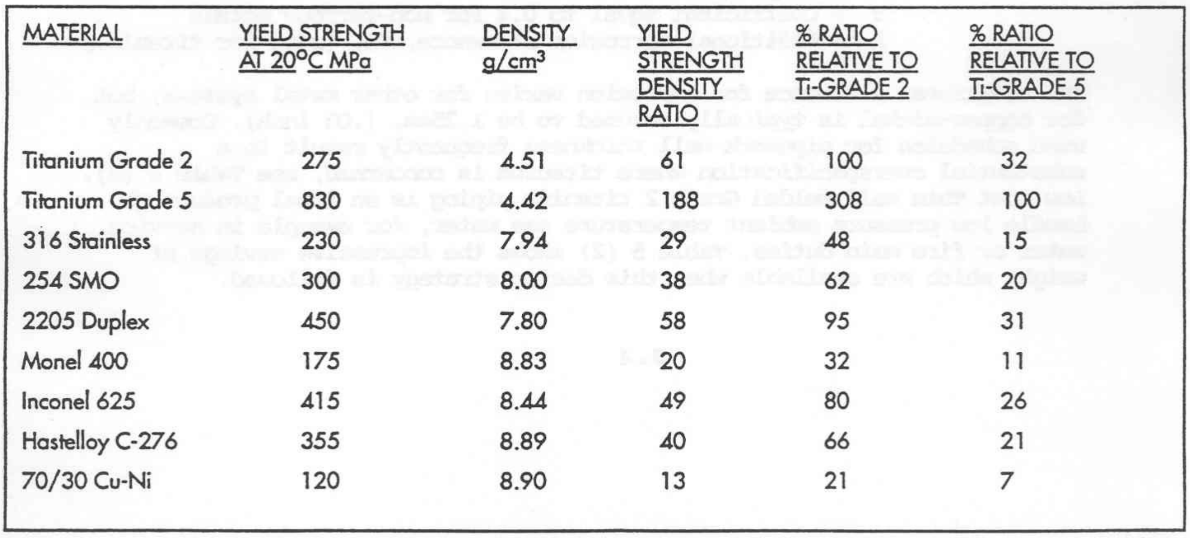
The comparative strength to weight ratios with other corrosion resistant alloys are given in Table 2.(1)



Designation	Grade 2	Grade 3	Grade 12	Grade 9	Grade 5	Beta C
Alloy type	Alpha	Alpha	Alpha	Alpha-Beta	Alpha-Beta	Beta
Composition %						
Oxygen Max.	0.25	0.35	0.25	0.12	0.2	0.12
Nitrogen Max	0.03	0.03	0.03	0.02	0.05	0.03
Hydrogen Max	0.015	0.015	0.015	0.015	0.015	0.015
Carbon Max	0.10	0.10	0.8	0.05	0.10	0.05
Iron Max	0.30	0.30	0.30	0.25	0.40	0.30
Aluminium	-	-	-	2.5-3.5	5.5-6.75	3.0-4.0
Vanadium	-	-	-	2.0-3.0	3.5-4.5	7.5-8.5
Molybdenum	-	-	0.2-0.4	-	-	3.5-4.5
Nickel	-	-	0.6-0.9	-	-	-
Chromium	-	-	-	-	-	5.5-6.5
Zirconium	-	-	-	-	-	3.5-4.5
Residuals each (total)	0.10 (0.4)	0.1 (0.4)	0.1 (0.4)	0.1 (0.4)	0.1 (0.4)	0.1 (0.4)
Mechanical Properties						
0.2% Proof Stress MPa	275	380	345	485	825	1170
min ksi*	40	55	50	70	120	170
UTS min MPa	345	450	483	620**	895	1240
ksi	50	65	70	90**	130	180
Elongation %	20	18	18	15	10	6
Hardness HV	160-200	180-220	170-240	260-320	330-390	360-420
Tensile Modulus GPa	103	103	103.5	103.5	113.8	103.4
ksi x 1000	14.9	14.9	15.0	15.0	16.6	15.0
Torsion Modulus GPa	44.8	44.8	42.7	43.0 i	42.1	41.3
ksi x 1000	6.5	6.5	6.2	6.2	6.1	6.0
Physical Properties						
Density gm/cc	4.51	4.51	4.51	4.48	4.43	4.82
lb/cu.in.	0.163	0.163	0.163	0.161	0.160	0.174
Thermal Expansion						
(0 - 200°C) 10^{-6}/°C	8.9	8.9	9.5	8.3	8.9	9.4
(32- 400°F) 10^{-6}/°F	4.9	4.9	5.3	4.6	4.9	5.2
Thermal Conductivity at Room Temp W/mK	16.4	16.4	19.0	8.0	6.7	6.3
BTU/ft.h.°F	9.47	9.47	10.98	4.62	3.87	3.64
BTU.in/ft^2.h.°F	114	114	132	55.5	46.5	43.7
Specific Heat at Room Temp J/Kg/°C	5.9	5.19	544	544	565	523
BTU/ lb/°F	0.123	0.123	0.13	0.13	0.135	0.125

* Ksi = lb/in^2 x 1000   ** higher strength levels for cold worked stress relieved material   i = interpolated value

TABLE 1



MATERIAL	YIELD STRENGTH AT 20°C MPa	DENSITY g/cm^3	YIELD STRENGTH DENSITY RATIO	% RATIO RELATIVE TO Ti-GRADE 2	% RATIO RELATIVE TO Ti-GRADE 5
Titanium Grade 2	275	4.51	61	100	32
Titanium Grade 5	830	4.42	188	308	100
316 Stainless	230	7.94	29	48	15
254 SMO	300	8.00	38	62	20
2205 Duplex	450	7.80	58	95	31
Monel 400	175	8.83	20	32	11
Inconel 625	415	8.44	49	80	26
Hastelloy C-276	355	8.89	40	66	21
70/30 Cu-Ni	120	8.90	13	21	7

TABLE 2

Using Design Codes Effectively

The design codes for items of plant and equipment, pipework, pressure vessels etc. set maximum stress levels against metal operating temperature, Table 3 which is from the ASME Boiler and Pressure Vessel code is typical of these, (See also appendix 1). Codes vary as to the fraction of the tensile strength used in the calculation of maximum allowable stress. ASME B31.1 uses one quarter of the UTS, ANSI more helpfully and economically uses one third af UTS. Code TBK 5/6 does not specifically cover titanium, but even more helpfully allows design stress levels to be the lower of:-

$$\frac{\text{Ultimate tensile strength at room temperature}}{2.4}$$

or:-

$$\frac{\text{Yield point at design temperature}}{1.35}$$

Directions in the application of this code include reduction of the allowable stress according to the location of welds and the extent of post weld non-destructive testing specified.

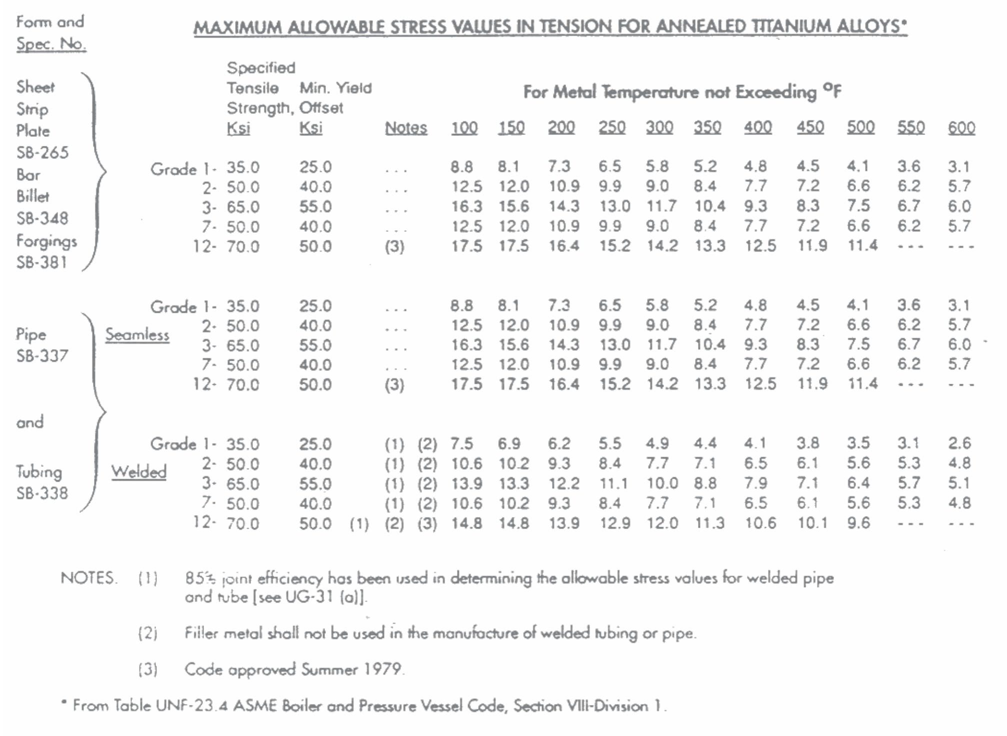
Application of code values to the associated design formula for metal thickness frequently produces surprising results. The ANSI B31.1 pipe wall thickness formula shows how the high strength and corrosion resistance of titanium combine to provide low weight, low cost, pipework of high integrity:-

$$Tm=\frac{PD}{2(S+PY)}+A$$

Tm = Minimum required wall thickness, mm
P = System Pressure, MPa
D = Pipe outside diameter, mm
S = Maximum allowable stress for material at design temperature, MPa
Y = Coefficient equal to 0.4 for non-ferrous metals
A = Additional corrosion allowance, mm (zero for titanium)

The additional allowance for corrosion varies for other metal systems, but for copper-nickel is typically assumed to be 1.25mm, (.05 inch). Commonly used schedules for pipework wall thickness frequently result in a substantial overspecification where titanium is concerned, see Table 4 (2). Low cost thin wall welded Grade 2 titanium piping is an ideal product to handle low pressure ambient temperature sea water, for example in service water or fire main duties. Table 5 (2) shows the impressive savings of weight which are available when this design strategy is followed.

Table 3:-



MAXIMUM ALLOWABLE STRESS VALUES IN TENSION FOR ANNEALED TITANIUM ALLOYS*

Form and Spec. No.		Grade	Specified Tensile Strength, Ksi	Min. Yield Offset Ksi	Notes	100	150	200	250	300	350	400	450	500	550	600
						For Metal Temperature not Exceeding °F										
Sheet Strip Plate SB-265 Bar Billet SB-348 Forgings SB-381		Grade 1-	35.0	25.0	. . .	8.8	8.1	7.3	6.5	5.8	5.2	4.8	4.5	4.1	3.6	3.1
		2-	50.0	40.0	. . .	12.5	12.0	10.9	9.9	9.0	8.4	7.7	7.2	6.6	6.2	5.7
		3-	65.0	55.0	. . .	16.3	15.6	14.3	13.0	11.7	10.4	9.3	8.3	7.5	6.7	6.0
		7-	50.0	40.0	. . .	12.5	12.0	10.9	9.9	9.0	8.4	7.7	7.2	6.6	6.2	5.7
		12-	70.0	50.0	(3)	17.5	17.5	16.4	15.2	14.2	13.3	12.5	11.9	11.4	- - -	- - -
Pipe SB-337 and Tubing SB-338	Seamless	Grade 1-	35.0	25.0	. . .	8.8	8.1	7.3	6.5	5.8	5.2	4.8	4.5	4.1	3.6	3.1
		2-	50.0	40.0	. . .	12.5	12.0	10.9	9.9	9.0	8.4	7.7	7.2	6.6	6.2	5.7
		3-	65.0	55.0	. . .	16.3	15.6	14.3	13.0	11.7	10.4	9.3	8.3	7.5	6.7	6.0
		7-	50.0	40.0	. . .	12.5	12.0	10.9	9.9	9.0	8.4	7.7	7.2	6.6	6.2	5.7
		12-	70.0	50.0	(3)	17.5	17.5	16.4	15.2	14.2	13.3	12.5	11.9	11.4	- - -	- - -
	Welded	Grade 1-	35.0	25.0	(1) (2)	7.5	6.9	6.2	5.5	4.9	4.4	4.1	3.8	3.5	3.1	2.6
		2-	50.0	40.0	(1) (2)	10.6	10.2	9.3	8.4	7.7	7.1	6.5	6.1	5.6	5.3	4.8
		3-	65.0	55.0	(1) (2)	13.9	13.3	12.2	11.1	10.0	8.8	7.9	7.1	6.4	5.7	5.1
		7-	50.0	40.0	(1) (2)	10.6	10.2	9.3	8.4	7.7	7.1	6.5	6.1	5.6	5.3	4.8
		12-	70.0	50.0	(1) (2) (3)	14.8	14.8	13.9	12.9	12.0	11.3	10.6	10.1	9.6	- - -	- - -

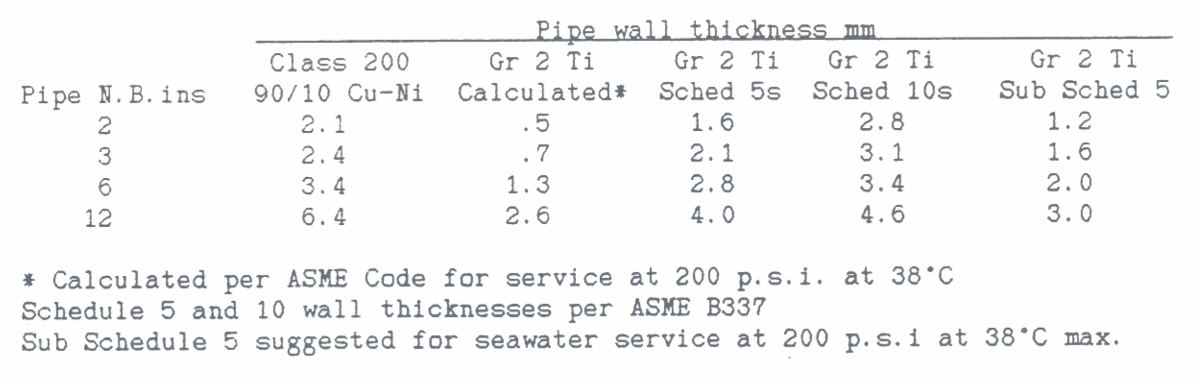
NOTES. (1) 85% joint efficiency has been used in determining the allowable stress values for welded pipe and tube [see UG-31 (a)].

(2) Filler metal shall not be used in the manufacture of welded tubing or pipe.

(3) Code approved Summer 1979.

* From Table UNF-23.4 ASME Boiler and Pressure Vessel Code, Section VIII-Division 1.

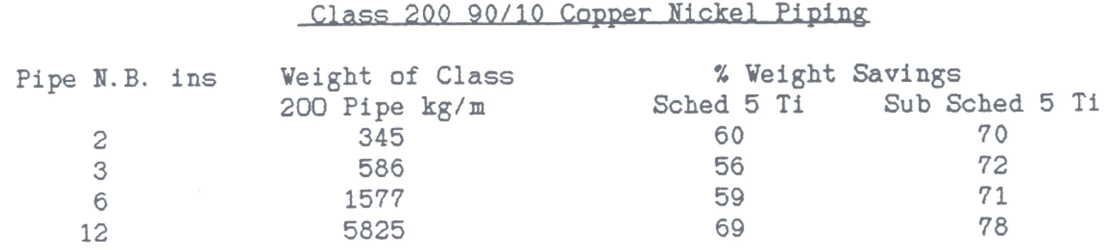
Table 4:- Pipe Wall Thicknesses for Grade 2 Titanium



	Pipe wall thickness mm				
Pipe N.B.ins	Class 200 90/10 Cu-Ni	Gr 2 Ti Calculated*	Gr 2 Ti Sched 5s	Gr 2 Ti Sched 10s	Gr 2 Ti Sub Sched 5
2	2.1	.5	1.6	2.8	1.2
3	2.4	.7	2.1	3.1	1.6
6	3.4	1.3	2.8	3.4	2.0
12	6.4	2.6	4.0	4.6	3.0

* Calculated per ASME Code for service at 200 p.s.i. at 38°C
Schedule 5 and 10 wall thicknesses per ASME B337
Sub Schedule 5 suggested for seawater service at 200 p.s.i at 38°C max.

Table 5:- Weight Savings Achieved When Thin-Wall Titanium Piping Replaces Class 200 90/10 Copper Nickel Piping



Pipe N.B. ins	Weight of Class 200 Pipe kg/m	% Weight Savings	
		Sched 5 Ti	Sub Sched 5 Ti
2	345	60	70
3	586	56	72
6	1577	59	71
12	5825	69	78

Physical Properties of Titanium and its Alloys

The physical properties of primary importance in mechanical design are the metal density, 4.51 gm/cc, (.163 lb/cu.in.) which is almost half that of other corrosion resistant alloys, and the modulus of elasticity.

In applications which are weight critical, the weight savings achievable with a properly designed titanium system will be appreciable. Where titanium is used to replace a heavier metal, e.g. retubing of heat exchangers and condensers, it may be necessary to modify the arrangements by which the unit is supported or suspended. (3)

Attention to the modulus is essential for the correct design and application of struts and supports, e.g. heat exchanger baffle spacing, (4) and unsupported pipe spans. The relatively low modulus is however a factor in the substantial resistance to shock which titanium and its alloys possess. Shock resistance is calculated from the maximum allowable stress divided by the square root of the product of the density and the elastic modulus. These two properties are both low for titanium and its alloys, and strengths are relatively high. The shock resistance of titanium is greater than that of most competing copper and nickel based corrosion resistant alloys. (2)

Fatigue, Fracture Toughness and Creep

Fatigue strength of smooth test specimens of titanium and its alloys is typically 50% - 60% of the tensile strength values. Notched specimen tests give lower values. Care is required in design and manufacture to avoid stress concentrating factors where cyclic stress is applied to high levels, or with great frequency. Poor surface finish, sharp sectional transitions, unblended radii and corners are typical conditions to avoid.

Commercially pure titanium and titanium alloys possess a low ductile to brittle transition temperature and have useful levels of impact and fracture toughness even at sub zero temperatures. The ASME Boiler and Pressure Vessel Code allows the rom temperature stress levels of Grades 1, 2, 3, 7 and 11 to be used in design for operational service down to -60°C, (-75°F).

Metallurgical and surface stability of titanium and its alloys is excellent within the working temperature range set by the value of useful strength. Creep values for commercially pure titanium to .1% plastic strain in 100,000 hours are approximately 50% those of the tensile strength at appropriate temperatures up to 300°C. Creep values for welds in commercially pure titanium lie in the same range as for base metal.

Thermal Performance of Titanium and Titanium Alloys

The thermal conductivity of titanium is low, and of the same order as that of stainless steel. Titanium heat exchangers can however be safely designed with low cost thin wall welded tubing, to the point where the tube resistance r^m is less than 2.5% of the total resistance, (Fig.1). The corrosion and general fouling resistance of titanium, and its ability to withstand higher fluid velocities permits design for equal and frequently superior overall heat transfer rates than can be achieved with full metals of higher thermal conductivity. The published (HEI) metal correction factors for titanium reflect lower values than achieved in many applications and may act as an artificial restraint to fully cost effective design, (Table 6), (4). Test results from titanium tubes installed in England showed titanium tubes to be operating at a heat transfer rate 9% higher than the clean calculated HEI rate. After 14 months service without cleaning the tubes were still performing with a cleanliness factor of 0.96. These levels of performance have also been confirmed by the Swedish State Power Board.

Figure 1: Total Resistance of Heat Exchanger Tubes

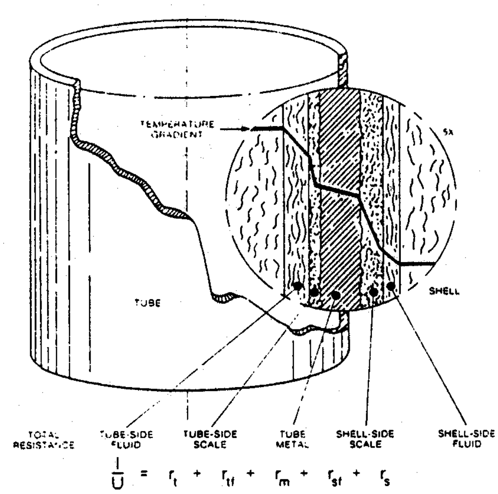
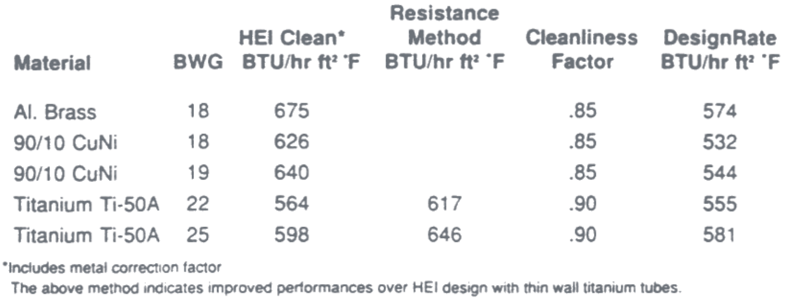


Table 6: Comparison of Heat Transfer Rates – HEI vs Resistance



Material	BWG	HEI Clean* BTU/hr ft² °F	Resistance Method BTU/hr ft² °F	Cleanliness Factor	DesignRate BTU/hr ft² °F
Al. Brass	18	675		.85	574
90/10 CuNi	18	626		.85	532
90/10 CuNi	19	640		.85	544
Titanium Ti-50A	22	564	617	.90	555
Titanium Ti-50A	25	598	646	.90	581

*Includes metal correction factor

The above method indicates improved performances over HEI design with thin wall titanium tubes.

Designing a Corrosion Resistant System

A stable, substantially inert, tenacious and permanent oxide film provides titanium with outstanding resistance to corrosion in a wide range cf aggressive media (5). The oxide film forms equally on welds as on parent metal, and on the industrial alloys as on commercially pure titanium. In situations where the oxide film is maintained or its formation supported - essentially in neutral to oxidising conditions over a wide range of pH and temperature, (Fig 2).- titanium will survive erosion, cavitation, pittings and crevice corrosion. Enhanced resistance is obtained from alloys containing nickel and molybdenum, - ASTM Grade 12, (Fig 3); or palladium, - ASTM Grades 7, 11 (Fig. 4) (6).

Long established application of titanium for vessels, pipework, heat exchangers and other process equipment in chemical, petrochemical and other plant has confirmed the following:-

1. Titanium requires no corrosion allowance.

The breakdown potential of titanium is very high in most environments, and pitting, which occurs when the potential of the metal exceeds the breakdown potential of its protective oxide film, is rarely encountered. The breakdown potential of titanium in phosphate and sulphate media is about 100 volts, in chlorides it is about 8 - 10 volts. Oxidising species, e.g. ferric ions, in the environment will enhance passivation. No corrosion allowance is required for titanium, and equipment should be designed to the minimum thickness of material to satisfy mechanical requirements.

2. Titanium resists erosion and cavitation

Seawater flowing at velocities up to 30 m/sec can be safely handled by titanium, (Fig 5). This permits safe increase of system flow rates, permitting design with smaller diameter pipework, and tighter pipework bend radii. The presence of sand or other abrasive particles has a small but significantly less effect on the erosion of titanium than on other metals, (Table 7). Titanium alloy castings used in hydrojet vehicles travelling at speeds around 50 mph, (80 km/hr) continue to demonstrate the outstanding resistance of the metal to erosion and cavitation damage.

3. Titanium is essentially immune to stress corrosion cracking

Commercially pure titanium grades 1 and 2 are essentially immune to stress corrosion cracking, (SCC), in sea water and chlorides. The few and specialised environments and media which may cause SCC in titanium, or in single titanium alloys have been well documented. Of these the one which gives rise to the most frequent concern is methanol. SCC failures of titanium have occurred in dry methanol, and in methanol/halide and methanol/acid mixtures. The presence of water above 1.5% maintains the passivity of commercially pure titanium. Titanium alloys vary in their susceptibility to SCC. Notched precracked specimens have had to be used in the laboratory to identify environments and rank alloys for susceptibility, with actual field failures being few or none. Ti-6Al-4V ELI, a low oxygen variant of the workhorse of titanium alloy range is ranked close in its performance to commercially pure titanium (5).

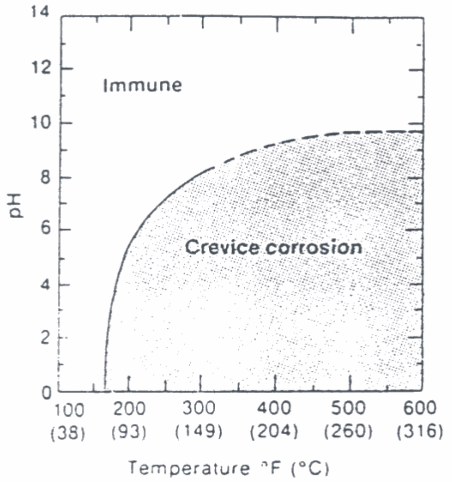


Figure 2 – Effect of Temperature and pH on Crevice Corrosion of Unalloyed Titanium (Ti-50A) in Saturated NaCl Brine

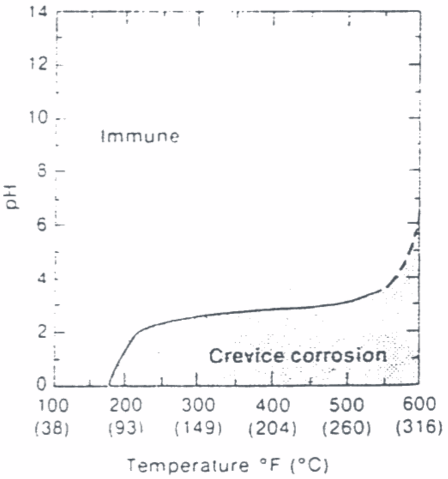


Figure 3 – Effect of Temperature and pH on Crevice Corrosion of TiCode-12 in Saturated NaCl Brine

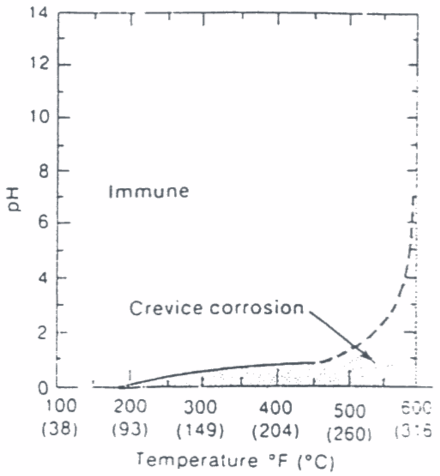


Figure 4 – Effect of Temperature and pH on Crevice Corrosion of Ti-Pd in Saturated NaCl Brine

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Table 7:

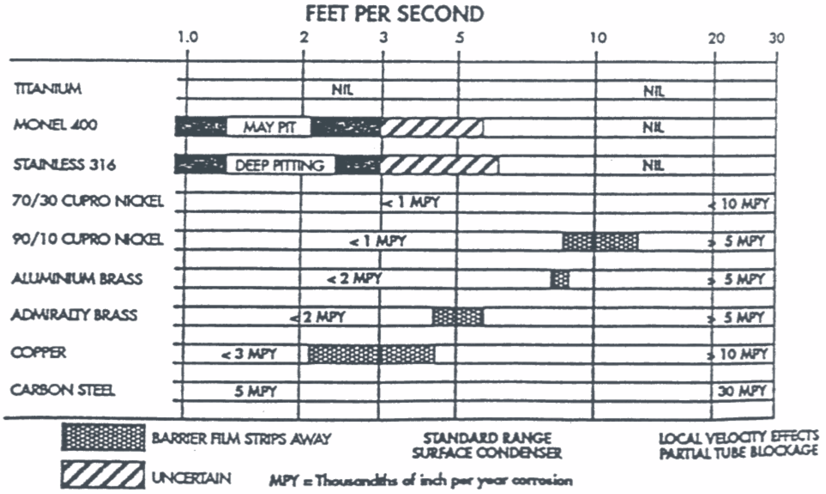
Erosion of Unalloyed Titanium in Seawater Containing Suspended Solids

Flow Rate ft/sec (m/sec)	Suspended Matter	Duration Hrs.	Corrosion / Erosion - mpy Gr. 2 Ti	70/30 Cu-Ni*	Al. Brass
23.6 (7.2)	None	10,000	Nil	Pitted	Pitted
6.6 (2)	40 g/l 60 Mesh Sand	2,000	0.1	3.9	2.0
6.6 (2)	40 g/l 10 Mesh Emery	2,000	0.5	Severe Erosion	Severe Erosion

* High iron, high manganese 70-30 cupro nickel.

Figure 5:

EFFECTS OF SEAWATER VELOCITY ON MATERIALS



4.Titanium is essentially resistant to corrosion fatigue

Commercially pure titanium suffers no significant loss af fatigue strength in sea water and other aqueous chloride media. (Table 8). Welds and parent metal, which are equally protected by the oxide film, typically exhibit smooth fatigue run out stress to tensile strength ratios of 50 - 60%.

5. Titanium will stay cleaner longer in fouling environments

Fouling factors between .90 and .99 are regularly used for titanium in heat exchangers. Marine biofouling will occur on titanium in static or slow moving sea water, but the integrity of the oxide film is maintained under the deposits which can be removed safely by mechanical methods or by regular or shock chlorination, or prevented by maintaining water velocity above 2 m/sec. It is popular belief that copper based alloys sucessfully resist biofouling. Fig. 6 shows that after a period of exposure, the fouling of cupronickel tubes used without chlorination approaches that of untreated titanium tubes.

In many other fouling situations, the oxide film will resist deposit adhesion, and facilitate cleaning. Recommended inhibited cleaning solutions should be specified for use when hard scale removal is necessary. In situations where there is persistent heavy system fouling intervals betwen cleaning may be extended by using low fin tube.

6. Titanium systems are self supporting

Titanium requires no inlet or outlet or bend erosion protection, and there is normally no requirement for system protection for corrosion by dosing, coatings, sacrificial anodes or impressed current cathodic protection, unless there is the possibility of galvanic corrosion of adjacent structures.

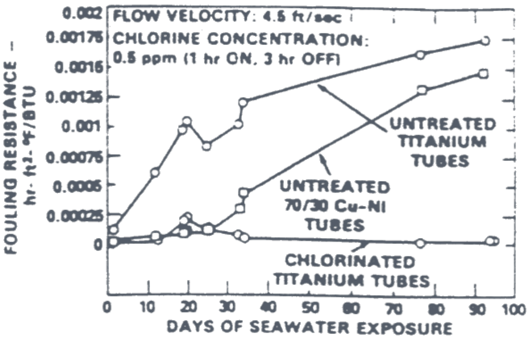
Table 8 Effect of Seawater on Fatigue Properties of Titanium

Alloy	Stress to cause Failure In 10^7 Cycles, *Ksi (MPa) Air	 Seawater
Ti-Gr.2	52 (359)	54 (372)
Ti-Gr.5	70 (480)	60 (410)

* Rotating beam fatigue tests on smooth, round bar specimens.

3.10

Fig. 6 Detrimental effect of seawater fouling with time on the heat transfer of titanium and cupro-nickel

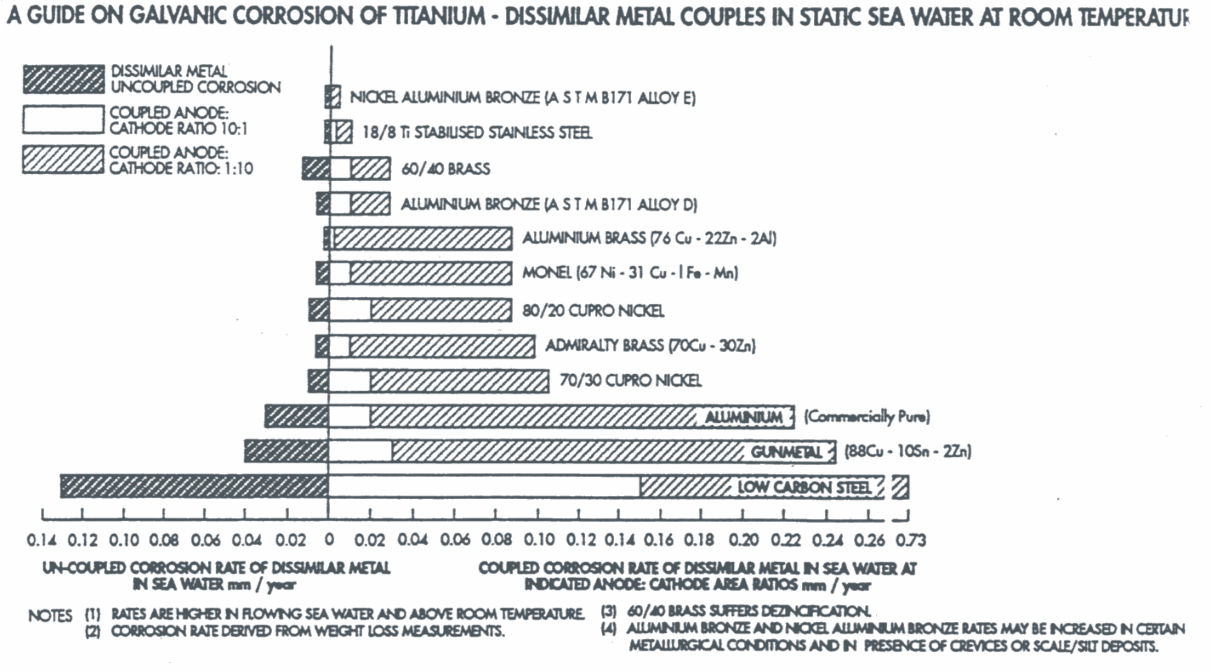


Practical Hazards of Working Systems

1. Galvanic Corrosion

It is rarely practicable to fabricate process systems entirely from one metal. Where titanium is incorporated into mixed metal plant or equipment, it will usually be the cathode if a galvanic couple exists, or is created. Alloys which are galvanically near compatible with titanium e.g. Inconel 625, Hastelloy C, 254SMO, Zeron 100, or composite materials may be selected to be in direct contact with titanium at joints. In their passive state several of the highly alloyed steels and nickel alloys are only marginally less noble than titanium, but if activated, for example by pitting, the rate of localised attack can be dramatic. Among commonly used structural corrosion resistant metals and alloys titanium will almost always be the cathode, (Fig 7).

Figure 7:-



A GUIDE ON GALVANIC CORROSION OF TITANIUM - DISSIMILAR METAL COUPLES IN STATIC SEA WATER AT ROOM TEMPERATUR

Design strategies to protect adjoining less noble parts of the system include, coating the titanium in the neighbourhood of the joint to reduce the effective cathode/anode ratio; application of cathodic protection to the base metal, but at no more than -1.0v SCE; electrical isolation of the titanium through the use of non conducting gaskets and sleeved bolts; installation of short easily replaced heavy wall sections of the less noble metal; chemical dosing. Conditions for rapid attack and failure of a less corrosion resistant material coupled to titanium may exist if only that metal is coated. Any coatings defects, damage or breakdown in localised areas will immediately cause problems unless cathodic or chemical protection is available or unless the adjoining titanium structure is also coated.

2. Hydrogen Absorption, (Hydriding)

Titanium oxide is an effective barrier to penetration of the metal by hydrogen. Titanium can absorb hydrogen from environments containing the gas. In practice hydrogen take-up is minimal or zero where more than 2% water vapour is present. Diffusion of hydrogen into titanium is very slow at temperatures below 80°C except where high residual or applied tensile stresses exist.

The most common cause of hydrogen absorption in reported cases comes from the generation of nascent hydrogen directly ont the surface of titanium by impressed current cathodic protection, (overzealously applied or uncontrolled), or galvanic corrosion of adjacent structures. Such absorption, occurring in the range of pH less than 3 and greater than 12 and with potentials more negative than -0.7 volts s.c.e. nay be aggravated by mechanical disruption of the oxide film or by the presence of smeared iron on the surface of titanium.

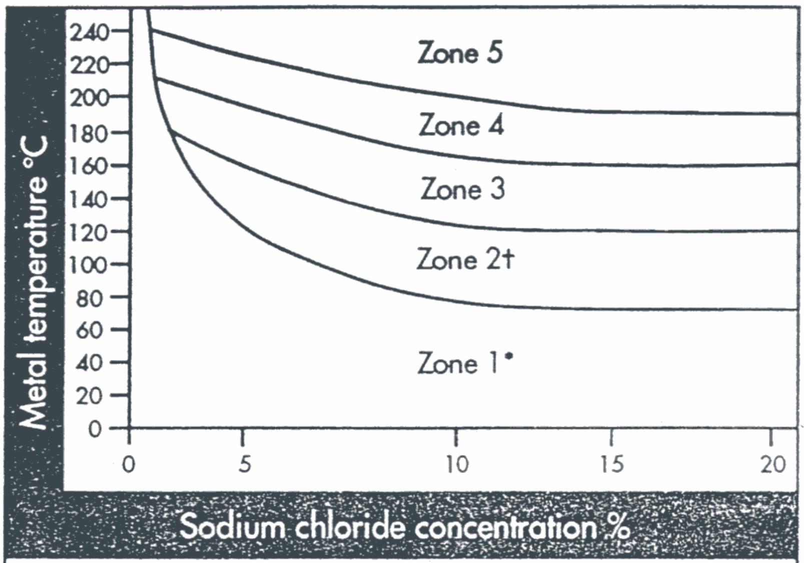
Where hydrogen absorption may occur, specification of a suitable oxidised finish is recommended. Films formed by thermal oxidation are the most resistant, oxide films produced by anodising are less effective in this respect, but the anodising process does have the benefit of removely selectively any impacted iron which might act as a point for hydrogen ingress (7). Disruption or dissolution of the oxide film allows hydrogen to diffuse into the base metal. Once the solubility limit of hydrogen in titanium is exceeded, (100 - 150 ppm for commercially pure titanium grade 2), titanium hydride will begin to precipitate. At temperatures not exceeding 80°C, (176°F), hydride will normally be restricted to the surface layers of the metal and experience in such cases indicates that this has little or no serious effect on the performance or properties of the metal. Cases of through section hydride formation, leading to embrittlement and cracking or failure under stress are very rare. Hydriding can be avoided by the proper design of equipment and control of operating conditions.

3. Crevice Corrosion

Localised pitting or corrosion, occuring in tight crevices and under scale or other deposits is a controlling factor in the application of unalloyed titanium. Attack will normally not occur on commercially pure titanium or industrial alloys below 70°C regardless of solution pH. Seawater and neutral brines above the boiling point will develop localised reducing acidic conditions, and pitting may occur. Enhanced resistance to reducing acid chlorides and crevice corrosion is available from alloy Grades 7, 11 and 12. (Fig 8). Most recent experience in testing alloys for FGD prescrubber application suggest that Fig 8 is perhaps too conservative in respect of the performance of Grade 7 in which it has been impossible to induce crevice corrosion even at very high chloride concentrations and low pH. Attention to design of flanged joints using heavy flanges and high clamping pressure, and the specification of gaskets, choosing elastic rather than plastic or hard materials may serve to prevent crevices developing. An alternative strategy is to incorporate a source of nickel, copper, molybdenum, or palladium into the gasket, as wire, foil, or as oxides impregnated into the gasket material.

Figure 8:

Immunity limits for crevice and pitting attack of titanium in sea-water and sodium chloride brines



	Commercially pure titanium	Grade 7 (Ti-0.2%Pd)
Zone 1*	Complete immunity	Complete immunity
Zone 2†	Crevice corrosion possible at titanium/titanium crevices.	Complete immunity
Zone 3	Crevice and pitting attack possible at acid pH levels	Crevice corrosion possible with titanium/tianium crevices at acid pH levels
Zone 4	Crevice and pitting attack probable	Crevice corrosion probable. Pitting attack possible at acid pH levels
Zone 5	Crevice and pitting attack probable	Crevice and pitting attack probable

* Power station condensers; refinery, offshore oil, and other sea water coolers; brine coolers; desalination heat rejection and recovery stages.

† Salt evaporation plant and deslination brine heater/recovery stages.

Design for Fabrication and Installation

In broad terms, anything that can be made in metal can be made in titanium. In practical terms, although construction in the solid metal may be possible, restraints on fabrication capacity and total cost may point to alternative solutions. Thin wall vessels and pipes will almost certainly be cost effective if made from solid titanium. Very heavy walled items will cost less if a stronger backing base metal is titanium clad. Heavy flange will prove to be expensive unless steel is used as a backer to a titanium taft or stub eend, (Fig 9). Long shafts may require extra bearing points if made from solid titanium, cladding of a stiffer base metal may provide a more effective answer, mechanically as well as economically. In each case consideration of all of the options should provide the optimum solution to combine requirements for mechanical performance, corrosion resistance and fabrication.

Design for Welding

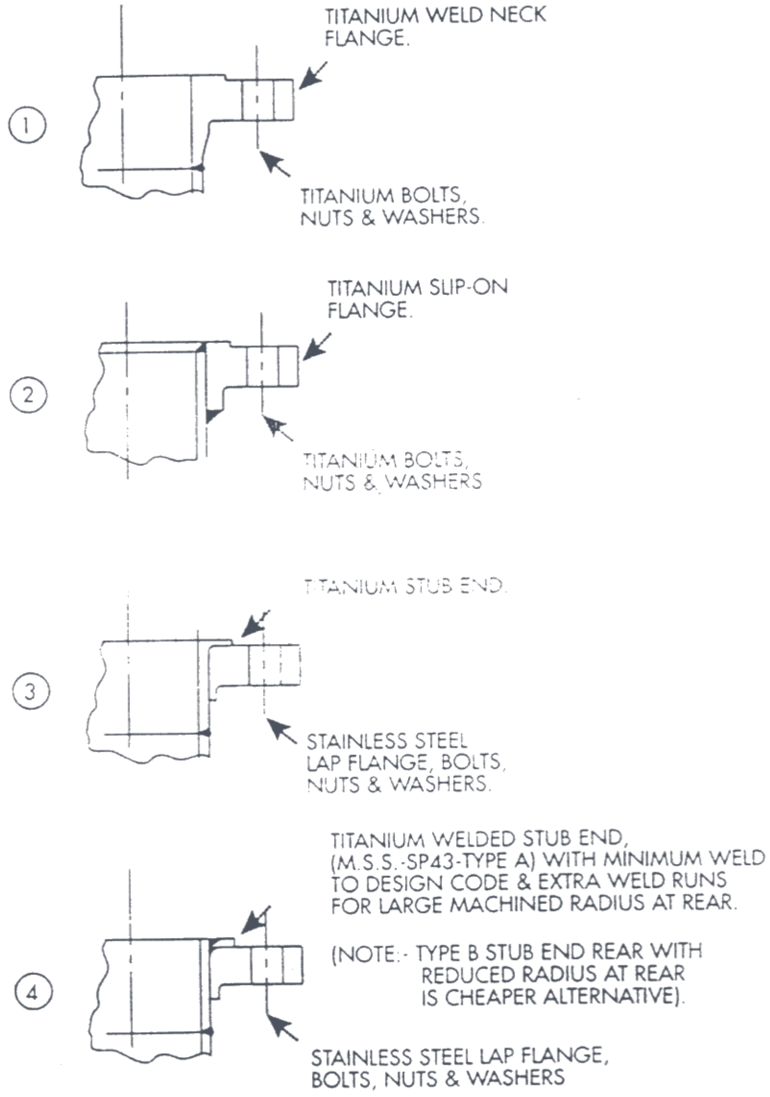
Weld joint designs for titanium are similar to those for other metals, and many excellent welding guides are now available to assist designers. Consultation with experienced fabricators is always worthwhile.

When titanium was first welded, very elaborate precautions were applied in order to minimise both distortion and weld oxidation. Practical experience and necessity has enabled these first and extreme precautions progressively to be relaxed, and open shop and field welding of large and small fabrications have been routine for many years. The provision of fully effective shielding may however be seen to be difficult if not impossible for field welds made in exposed locations such as on offshore platforms. A detailed evaluation of the effect of oxygen pick up which might occur in such circumstances has shown commercially pure titanium to be tolerant of up to 0.6% air contamination of the shielding gas, the properties of such welds and parent metal in the heat affected zone remaining within the allowable specification range.(8)

Whilst a good standard of primary and secondary inert gas shielding is normal practice, there may be fabrication design requirements where back shielding of welds is impossible. The fillet welding in situ of fitted linings is an example. The application of titanium liners in flue gas desulphurisation plant using Titaniun Resista-Clad Plate has generated considerable experience of satisfactory post weld performance where back shielding was impracticable. The development of this procedure was supported up by an evaluation programme in which horizontal vertical and overhead welds were made on 1.6mm thick overlapping sheets, without inert gas back shielding. The results indicated that although some measurable oxygen pickup occured in the absence of backshielding, that accetable engineering welds were produced, with strengths more than adequate for the FGD liner service application, (Table 8). Comparable considerations would apply to the lining or external cladding of large diameter steel pipes for offshore service.

Figure 9:

FLANGE ARRANGEMENTS IN DESCENDING ORDER OF COST.



⑤ AS ③ BUT WITH MILD STEEL EPOXY COATED FLANGE, BOLTS, NUTS & WASHERS.

⑥ AS ④ BUT WITH MILD STEEL EPOXY COATED FLANGE, BOLTS, NUTS & WASHERS.

Table 8:

EVALUATION OF TITANIUM FILLET WELDS MADE WITHOUT BACKSHIELDING

Material:-

Commercially pure titanium Grade 2 .063", (1.6mm) thick

Weld type:-

Fillet on overlapping sheets with weld joint gaps 0 to .063"

Weld runs:-

Horizontal, vertical, overhead

Weld wire:-

Titanium Grade 2, but Grade 1 proposed for field use

Weld gas:-

Argon, but helium proposed for overhead welding

Oxygen pick-up:-

Parent metal	.12%
ASTM Spec max for Grade 2	.25%
Av weld oxygen in worst case	.15%
Av weld oxygen in trials	.13%

Worst case = .063" gap near end of seam

Weld strength tests:-

Tensile tests were conducted on .25" wide,(6.5mm) samples

Load to break strongest weld	1234lbs	559kg
Load to break weakest weld	704lbs	319kg
Av load all tests	1002lbs	454kg
(Load to break unwelded parent	787lbs	357kg)

Stress Relieving

Vessels and other fabrications in commercially pure titanium will normally not require stress relief. Machined parts with very tight tolerances may be stress relieved immediately prior to finishing to size. Stress relieving should also be considered where fatigue may be a factor in service. Generally, low temperatures, 500°C - 525°C for one hour per 25mm of section are adequate. Higher temperatures up to 600°C are sometimes recommended, but generate a greater level of oxidation, without necessarily giving any improved result over the lower temperature treatment.

The Cost Element of Design

The first cost of equipment properly designed in titanium is never as high as the price, (by weight) of the metal suggests. Most designs are based on use of metal by surface area rather than by weight, and the strength, lower density and corrosion resistance of titanium are all factors which contribute positively towards cost reduction. In the following examples titanium is compared with nominally lower cost, "heavy-weight" competitors in sheet and pipe applications:-

Sheet cost by weight

....Titanium £15 per kilo	Competitor £10 per kilo

Cost per standard sheet 2 1/2 m x 1m x 1.5m

....Titanium £255	Competitor £340

The corrosion resistance of titanium especially resistance to pitting may enable the designer to specify a thinner gauge of metal. Titanium of 1mm thickness may be adequate and at £170 per standard sheet, costs half the price of the apparently cheaper competitive material!

Pipe and tube are normally quoted and sold per metre, but there is a danger on projects where substantial tonnages of pipe are required that price by weight may be used to budget total first cost. There is a serious danger that titanium would be excluded on this basis. A most studied approach would almost certainly show not only lower first cost for titanium but also substantial life cost savings and downstream technical benefits.

Kilo for kilo a titanium pipe of the same diameter and scheduled will be almost twice as long as pipe made from any one its most dense competitors. Reduction of the schedule as shown in Table 5 can cut pipe by weight by over 70%, with a substantial reduction in the total purchase price.

First cost is however only one part of the whole cost equation. Maintenance and downtime costs, wich may be a very significant element in plant designed for a long service life, are another. Titanium inherently saves cost through reliable performance. Welded titanium tube supplied by Timet for power plant surface condenser use has for some time been sold with a 40 year performance guarantee. More recently a similar guarantee has been extended to Grade 2 and Grade 3 tubeplates for the same application. Many of the earlier installations of welded tube have now outlived their original guarantee periods several times over.

Availability of Titanium

As more titanium is used in an increasing variety of applications, questions of supply and price inevitably arise. There is however no cause for any concern. Titanium dioxide, (rutile), ore as a mineral resource is available at relatively low and stable price worldwide. Titanium is the fourth most abundant structural metal in the earths crust. The extraction of titanium is a multi-strage process, the first recognisably metallic product being "sponge". This product has no value as an engineering material, and needs to be consolidated and melted to produce ingots from material semi-finished and finished products may be manufactured.

Titanium sponge

Sponge is frequently in the news and its availability and price are sometimes but not always Correctly used as a yardstick of the capacity of the industry and for product price trends. Sponge is offered from time to time on metal markets at a price depending upon the quality of the product, th situation of the seller and the state of the market. Not all sponge is suitable for conversion to specific grades and alloys of titanium.

Titanium extraction and sponge production are specialised operations, sponge melting and the subsequent conversion of ingot to semi-finished products may be carried out wherever suitable facilities exist. Total productive capacity for titanium worldwide substantially exceeds the long term forecasts of demand. In these circumstances long term price stability may be excepted. Titanium, primarily sourced in friendly countries with democratic regimes, has never been subject to crisis or politically motivated pricing factors.

Production and Range of Semi-finished Products

Titanium ingots are the proper starting point of metal manufacture and are handled as the other industrial metals and alloys by forging or rolling to produce intermediate billet or slab. Billet provides the material for manufacture of forgings, bar, wire, and extruded ar rolled/drawn seamless tube and pipe. Slab provides the starting material for plate, sheet, welded tube and welded pipe. Castings are produced directly from ingot. Cast weldments enable large components exceeding the limits of individual casting weight, (typically 750Kg), to be supplied. A combination of forging, machining and fabrication provides the route to all requirements for engineering products.

Some Practical Guidelines to Design Cost Control

Do:-

Check available standard products and specifications to obtain best availability and lowest cost

Use design strategies based on using minimum material thickness

Exploit corrosion resistant characteristics to the full

Consider the use of liners and cladders in preference to solid design where heavy sections are unavoidable

Use welded fabrication where practicable in preference to forging and machining

Consult suppliers and fabricators at the earliest stage of design

Do not:-

Simply substitute titanium into existing designs

Budget for titanium project costs by weight, especially not by the weight of steel or copper alloys

Specify little used alloys or forms

Conclusion

Titanium has many existing and potential applications across a wide range of industries. The metal should be considered wherever corrosion is a problem of weight a factor. Titanium offers designers a unique combination of useful mechanical, physical and corrosion resistant properties which can be exploited to improve product and process quality and service life of equipment working in the most demanding environments. Effective design can be achieved by attention to the practical differences, the most relevant of which have been discussed, and which distinguish titanium from the traditional engineering metals.

Acknowledgements

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APPENDIX 1

SAFE INTERNAL WORKING PRESSURES lbs/in^2 FOR ANNEALED ASTM Gr. 2 AND Ti-Pd ASTM Gr. 7 WELDED TUBING AT 100°F.*

OUTSIDE DIAMETER OF TUBE

WALL (INCH)	1/2"	5/8"	3/4"	7/8"	1"	1-1/4"	1-1/2"	1-3/4"	2"	2-1/4"	2-1/2
0.020	805	650	545	470	410	330	275				
0.025	1000	805	675	585	510	410	345	295			
0.028	1110	900	755	650	570	460	385	330	290		
0.032	1260	1020	860	740	650	525	440	375	330	295	
0.035	1365	1110	935	805	710	570	480	410	360	320	290
0.042	1615	1315	1110	960	845	680	570	490	430	385	345
0.049	1855	1515	1280	1110	980	790	665	570	500	445	405
0.065			1660	1445	1275	1035	870	750	660	590	530
0.072			1825	1585	1405	1140	960	830	730	650	590
0.083					1600	1300	1100	950	835	745	675

* Calculated from $P = \frac{St}{R+0.6t}$ where S is the design stress for Gr. 2 welded tubing, R is 1/2 the tube outside diameter, and t is the tube wall thickness.

MULTIPLYING FACTORS TO DETERMINE SAFE INTERNAL WORKING PRESSURES OF ANNEALED, WELDED TITANIUM TUBING AT ELEVATED TEMPERATURES *

FOR METAL TEMPERATURES NOT EXCEEDING, DEG. F

	100	150	200	250	300	350	400	450	500	550	600
(ASTM Gr. 2) (ASTM Gr. 7)	1.000	.960	.872	.792	.726	.672	.616	.576	.528	.496	.456
(ASTM Gr. 3)	1.304	1.248	1.144	1.040	.936	.832	.744	.664	.600	.536	.480
(ASTM Gr. 12)	1.400	1.400	1.312	1.216	1.136	1.065	1.000	.952	.912		

* Select safe working pressure (SWP) for Grade 2 tubing of desired diameter and wall thickness. Then use multiplying factor from this table to determine SWP for desired alloy and temperature.

EXAMPLE: Determine SWP for Grade -12 1" x .065" welded tubing at 350°F. From Table above SWP for 1" x .065" Grade 2 welded tubing at 350°F. is 1275 PSI.
The multiplying factor for Grade -12 at 350°F. is 1.065.
The SWP for Grade -12 at 350°F. is calculated as 1.065 x 1275 = 1357 PSI