TITANIUM

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Titanium, The Choice

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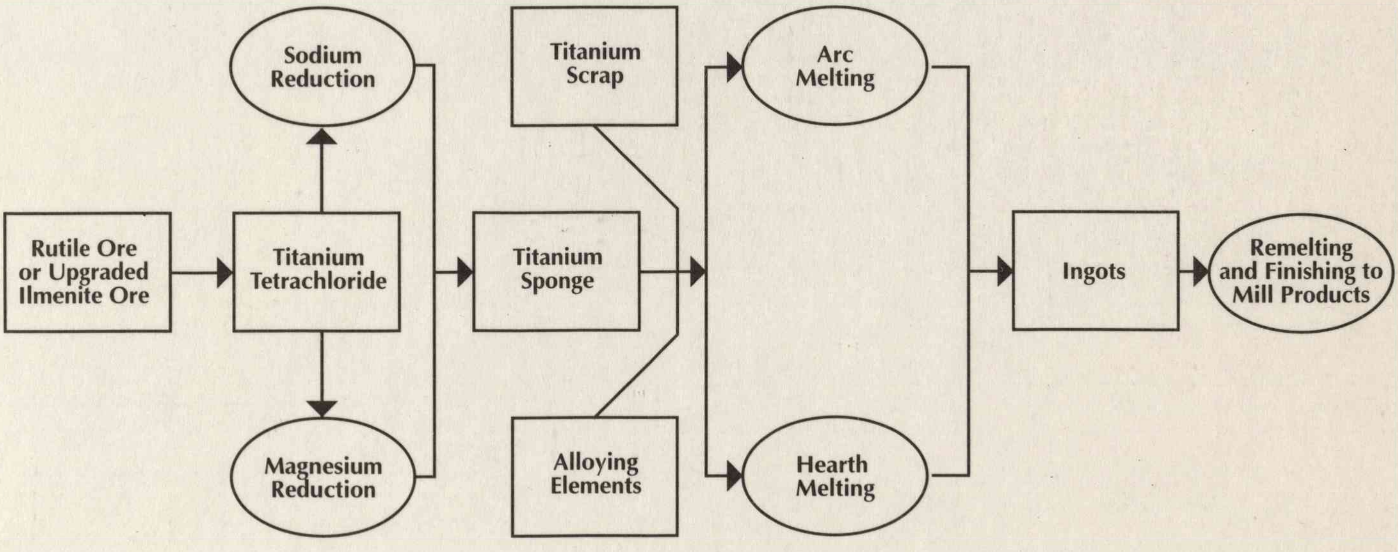
Process Flow Chart of Titanium Production



Process Flow Chart of Titanium Production reprinted with permission of RMI Company, Niles, Ohio

Introduction

It was almost 200 years ago that titanium was first isolated and named after the powerful mythological first sons of the Earth—the Titans. The industry as we know it today is over 40 years old. Titanium is most commonly associated with jet engines and airframes, but the most recent media attention has been given to fittings for prosthetic devices and the artificial heart.

Once judged to be expensive, titanium, in life-cycle costing, is now more often seen to be economical. The key to its cost-effective use is to utilize its unique properties and characteristics in the design rather than to substitute titanium for another metal.

Titanium is the world's fourth most abundant structural metal. It is found in North America, South America, Europe, Africa, U.S.S.R, China and Australia in the forms of ilmenite, rutile and other ores. The most widely used means of winning the metal from the ore is the Kroll process which uses magnesium as a reducing agent. Sodium is also used as a reducing agent by some producers.

To produce titanium, the basic ore, usually rutile (TiO_2) is converted to sponge in two distinct steps. First, TiO_2 is mixed with coke or tar and charged in a chlorinator. Heat is applied and chlorine gas is passed through the charge. The titanium ore reacts with the chlorine to form $TiCl_4$, titanium tetrachloride, and the oxygen is removed as CO and CO_2. The resultant crude $TiCl_4$ produced is a colorless liquid and is purified by continuous fractional distillation. It is then reacted with either magnesium or sodium under an inert atmosphere. This results in metallic titanium sponge, and either magnesium or sodium chloride which is reprocessed and recycled.

Melting is the second step. Titanium is converted from sponge to ingot by first blending crushed sponge with the desired alloying elements to insure uniformity of composition, and then pressing into briquets which are welded together to form an electrode. The electrode is melted in a consumable electrode vacuum arc furnace where an arc is struck between the electrode and a layer of titanium in a water-cooled copper crucible. The molten titanium on the outer surface solidifies on contact with the cold wall, forming a shell or skull to contain the molten pool. The ingot is not poured, but solidifies under vacuum in the melting furnace. To insure homogeneity of the final ingot, a second or sometimes a third melting operation is applied.

The properties and characteristics which are important to design engineers are:

☐ **Excellent Corrosion Resistance**
Titanium is immune to corrosive attack by salt water or marine atmospheres. It also exhibits exceptional resistance to a broad range of acids, alkalis, natural waters and industrial chemicals.

☐ **Superior Erosion Resistance**
Titanium offers superior resistance to erosion, cavitation or impingement attack. Titanium is at least twenty times more erosion resistant than the copper-nickel alloys.

☐ **High Heat Transfer Efficiency**
Under "in service" conditions, the heat transfer properties of titanium approximate those of admiralty brass and copper-nickel. There are several reasons for this:
(1) Titanium's higher strength permits the use of thinner walled equipment.
(2) There appear to be unusual and beneficial characteristics in titanium's inherent oxide film.
(3) The relative absence of corrosion in media where titanium is generally used leaves the surface bright and smooth for improved lamellar flow.
(4) Titanium's excellent erosion-corrosion resistance permits significantly higher operating velocities.

☐ **Superior Strength-to-Weight Ratios**
The densities of titanium-based alloys range between .160 lb/in^3 (4.43 gm/cm^3) and .175 lb/in^3 (4.85 gm/cm^3). Yield strengths range from 25,000 psi (172 MPa) commercially pure (CP) Grade 1 to above 200,000 psi (1380 MPa) for heat treated beta alloys.

The combination of high strength and low density results in exceptionally favorable strength-to-weight ratios for titanium-based alloys. These ratios for titanium-based alloys are superior to almost all other metals and become important in such diverse applications as deepwell tubestrings in the petroleum industry and surgical implants in the medical field.

Physical Metallurgy Considerations

To understand the microstructure of any alloy system it is necessary to outline the phase relationships and constitution of the system being studied.

Titanium can exist in two crystal forms. The first is alpha which has a hexagonal close-packed crystal structure and the second is beta which has a body-centered cubic structure. In unalloyed titanium, the alpha phase is stable at all temperatures up to 1620°F. (880°C.) where it transforms to the beta phase. This temperature is known as the beta transus temperature. The beta phase is stable from 1620°F. (880°C.) to the melting point.

As alloying elements are added to pure titanium, the elements tend to change the temperature at which the phase transformation occurs and the amount of each phase present. Alloy additions to titanium, except tin and zirconium, tend to stabilize either the alpha or the beta phase. Elements called alpha stabilizers stabilize the alpha phase to higher temperatures and beta stabilizers stabilize the beta phase to lower temperatures.

Alloy Classifications

There are three structural types of titanium alloys:

☐ **Alpha** alloys are non-heat treatable and are generally very weldable. They have low to medium strength, good notch toughness, reasonably good ductility and possess excellent mechanical properties at cryogenic temperatures. The more highly alloyed alpha and near-alpha alloys offer optimum high temperature creep strength and oxidation resistance as well.

☐ **Alpha-Beta** alloys are heat treatable and most are weldable. Their strength levels are medium to high. Their hot-forming qualities are good, but the high temperature creep strength is not as good as in most alpha alloys.

☐ **Beta** or near-beta alloys are readily heat treatable, generally weldable, capable of high strengths and good creep resistance to intermediate temperatures. Excellent formability can be expected of the beta alloys in the solution treated condition. Beta-type alloys have good combinations of properties in sheet, heavy sections, fasteners and spring applications.

A full description of the properties of the alpha, alpha-beta and beta alloys is contained in Appendix I.

Why Do We Use Titanium

Titanium and titanium alloys have proven to be technically superior, highly reliable and cost-effective in a wide variety of chemical, industrial, marine and aerospace applications. Titanium is utilized in many critical services due to its unique set of properties.

Corrosion Resistance

The environmental resistance of titanium depends primarily on a very thin, tenacious and highly protective surface oxide film. Titanium and its alloys develop very stable surface oxides with high integrity, tenacity and good adherence. The surface oxide of titanium will, if scratched or damaged, immediately reheal and restore itself in the presence of air or water.

The protective passive oxide film on titanium (mainly TiO_2) is very stable over a wide range of pH, potential and temperature and is especially favored as the oxidizing character of the environment increases. For this reason, titanium generally resists mildly reducing, neutral and highly oxidizing environments up to reasonably high temperatures. It is only under highly reducing conditions where oxide film breakdown and resultant corrosion may occur.

The presence of common oxidizing background or contaminating species often maintain or extend the useful performance limits of titanium in many highly aggressive environments. These inhibitive species include air, oxygen, ferrous alloy corrosion products, other specific metallic ions, and/or other dissolved oxidizing compounds. Titanium's already wide range of application can be expanded by alloying with certain noble elements or by impressed anodic potentials (anodic protection).

Also titanium generally exhibits superior resistance to chlorides and various forms of localized corrosion. Titanium alloys are considered to be essentially immune to chloride pitting and intergranular attack; and are highly resistant to crevice and stress corrosion.

Another major benefit to the designer is the fact that weldments, heat affected zones and castings of many of the industrial titanium alloys exhibit corrosion resistance equal to their base metal counterparts. This is attributable to the metallurgical stability of the leaner titanium alloys and the similar protective oxide which forms on titanium surfaces despite microstructural differences.

The following sections review the corrosion behavior of titanium in the more common service environments encountered in industry. Performance of titanium in other environments or more complex conditions may require further inquiry, consultations, or even testing.

Chlorine, Chlorine Chemicals and Other Halogen Compounds

Titanium alloys are highly resistant to wet (aqueous) chlorine, bromine, iodine and other chlorine chemicals because of their strongly oxidizing natures. Titanium's outstanding resistance to aqueous chlorides has been the primary historical incentive for utilizing titanium in industrial service. In many chloride and bromide-containing environments, titanium has cost-effectively replaced stainless steels, copper alloys and other metals which have experienced severe localized corrosion and stress corrosion cracking.

Chlorine Gas Titanium is widely used to handle moist or wet chlorine gas, and has earned a reputation for outstanding performance in this service. The strongly oxidizing nature of moist chlorine passivates titanium resulting in low corrosion rates. Proper titanium alloy selection offers a solution to the possibility of crevice corrosion when wet chlorine service temperatures exceed 155°F. (70°C.).

Dry chlorine can cause rapid attack of titanium and may even cause ignition if moisture content is sufficiently low. However, as little as one percent water is generally sufficient for passivation or repassivation after mechanical damage to titanium in chlorine gas under static conditions at room temperature.

Chlorine Chemicals and Chlorine Solutions Titanium is fully resistant to solutions of chlorites, hypochlorites, chlorates, perchlorates and chlorine dioxide. It has been used to handle these chemicals in the pulp and paper industry for many years with no evidence of corrosion.

Titanium is used in chloride salt solutions and other brines over the full concentration range, especially as temperatures increase. Near nil corrosion rates can be expected in brine media over the pH range of 3 to 11. Oxidizing metallic chlorides, such as $FeCl_3$, $NiCl_2$, or $CuCl_2$, extend titanium's passivity to much lower pH levels.

A possible limiting factor of titanium alloy application in aqueous chlorides can be crevice corrosion in metal to metal joints, gasket to metal interfaces or under process stream deposits. Given these potential crevices in hot chloride containing media, localized corrosion of unalloyed titanium and other alloys may occur depending on pH and temperature.

Service and laboratory-based guidelines, shown in Figure 1, have been developed to aid in proper alloy selection. These guidelines apply to most types of chloride solutions over a wide range of salt concentrations. As indicated in Figure 1, the Grade 12 and 7 titanium alloys offer improved crevice corrosion resistance when solution pH increases or temperature increases.

Halogen Compounds Similar considerations generally apply to other halogens and halides compounds. Special concern should be given to acidic aqueous fluorides and gaseous fluorine environments which can be highly corrosive to titanium alloys.

Other Salt Solutions

Titanium alloys exhibit excellent resistance to practically all salt solutions over a wide range of pH and temperatures. Good performance can be expected in sulfates, sulfites, borates, phosphates, cyanides, carbonates, and bicarbonates.

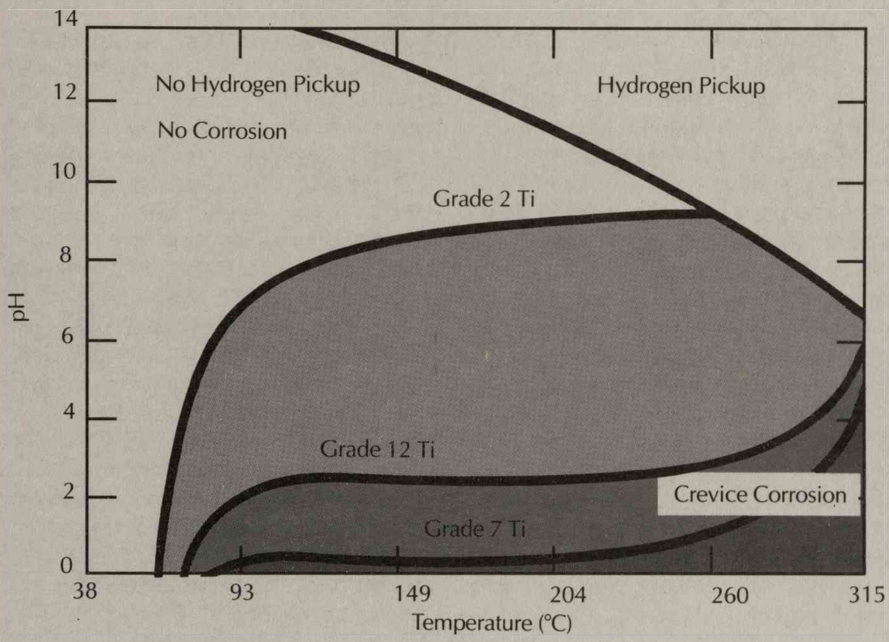


Figure 1: Temperature-pH guidelines for avoiding crevice corrosion of titanium alloys in concentrated NaCl brines.

Similar results can be expected with oxidizing anionic salts such as nitrates, molybdates, chromates, permanganates, and vanadates; and also with oxidizing cationic salts, including ferric, cupric, and nickelous compounds.

Resistance to Waters

Fresh Water/Steam Titanium alloys are highly resistant to water, natural waters and steam to temperatures in excess of 570°F. (300°C.) Excellent performance can be expected in high purity water, fresh water and body fluids. Typical contaminants found in natural water streams, such as iron and manganese oxides, sulfides, sulfates, carbonates and chlorides do not compromise titanium's performance. Titanium remains totally unaffected by chlorination treatments used to control biofouling.

Seawater Titanium is fully resistant to natural seawater regardless of chemistry variations and pollution effects (i.e. sulfides). Twenty year corrosion rates well below .01 mpy have been measured on titanium exposed beneath the sea, in marine atmospheres, and in splash or tidal zones. In the sea, titanium alloys are immune to all form of localized corrosion, and withstand seawater impingement and flow velocities in excess of 100 ft/sec (0.0003 mm/y). (See Table 1). Abrasion and cavitation resistance of these alloys is outstanding, explaining why titanium provides total reliability in many marine and naval applications. In addition, the fatigue strength and toughness of many titanium alloys are unaffected in seawater and lean titanium alloys are immune to seawater stress corrosion.

Titanium tubing has been used with great success for more than 20 years in seawater-cooled heat exchangers in the chemical, oil refining and desalination industries. The pH-temperature guidelines for crevice corrosion presented in Figure 1 are generally applicable to seawater service as well.

When in contact with other metals, titanium alloys are not subject to galvanic corrosion in seawater. However, titanium may accelerate attack on active metals such as steel, aluminum, or copper alloys. The extent of galvanic corrosion will depend on many factors such as anode to cathode ratio, seawater velocity and seawater chemistry. The most successful strategies eliminate this galvanic couple by using more-resistant compatible, passive metals with titanium, all-titanium construction, or dielectric (insulating) joints. Other approaches for mitigating galvanic corrosion have also been effective: coatings, linings and cathodic protection.

Resistance to Acids

Oxidizing Acids In general, titanium has excellent resistance to oxidizing acids, such as nitric and chromic, over a wide range of temperatures and concentrations.

Table 2: Corrosion of Titanium and Stainless Steel Heating Surfaces Exposed to Boiling 90% HNO_3

Metal Temperature	*Gr. 2 Ti*	*304L SS*
(°C)	*(mm/y)*	*(mm/y)*
116	0.03-0.17	3.8-13.2
135	0.04-0.15	17.2-73.7
154	0.03-0.06	18.3-73.7

Nitric Acid Titanium is used extensively for handling nitric acid in commercial applications. Titanium exhibits low corrosion rates in nitric acid over a wide range of conditions (Table 2). At boiling temperatures and above, titanium's corrosion resistance is very sensitive to nitric acid purity. Generally, the higher the contamination and the higher the metallic ion content of the acid, the better titanium will perform. This is in contrast to stainless steels which are often adversely affected by acid contaminants. Since titanium's

Table 1: Comparison of Alloy Erosion-Corrosion Resistance at Various Seawater Locations

~~Sheet; Plate; Bar; Billet;~~ Wire

Location	*Flow Rate*	*Duration*	*Corrosion Rate — mm/y* Gr. 2 Ti	70-30 Cu-Ni	Aluminum
	(m/sec)	*(Months)*			
Brixham Sea	9.8	12	<0.0025	0.3	1.0
Kure Beach	1.0	54	7.5×10^{-7}	—	—
	8.5	2	1.2×10^{-4}	0.05	—
	9.0	2	2.8×10^{-4}	2.1	—
	7.2	1	5.0×10^{-4}	0.12	—
Wrightsville Beach	0.6-1.3	6	1.0×10^{-4}	0.02	—
	9.10	2	1.8×10^{-4}	—	—

own corrosion product (Ti^{+4}) is highly inhibitive, titanium often exhibits superb performance in recycled nitric acid streams such as reboiler loops.

One user cites an example of a titanium heat exchanger handling 60% HNO_3 at 380°F. (193°C.) and 300 psi (2.1 MPa) which showed no signs of corrosion after more than two years of operation. Titanium reactors, reboilers, condensers, heaters and thermowells have been used in solutions containing 10 to 70% HNO_3 at temperatures from boiling to 600°F. (315°C.).

Red Fuming Nitric Acid Although titanium has excellent resistance to nitric acid over a wide range of concentrations and temperatures, it should not be used with red fuming nitric acid because of the danger of pyrophoric reactions. Minimum water content and maximum NO_2 concentration (NO_2/NO ratio) guidelines for avoiding pyrophoric reactions in this particular acid have been developed.

Reducing Acids Titanium alloys are generally very resistant to mildly reducing acids, but can display severe limitations in strongly reducing acids. Mildly reducing acids such as sulfurous acid, acetic acid, terepthalic acid, adipic acid, lactic acid and many organic acids generally represent no problem for titanium over the full concentration range.

However, relatively pure, strong reducing acids, such as hydrochloric, hydrobromic, sulfuric, phosphoric, oxalic and sulfamic acids can accelerate general corrosion of titanium depending on acid temperature, concentration and purity. The Ti-Pd alloy offers dramatically improved corrosion resistance under these severe conditions. In fact, Ti-Pd often compares quite favorably to nickel alloys in dilute reducing acids as shown in Table 3.

Table 3: Comparative Corrosion Resistance of Ti-Pd and Ni-Cr-Mo Alloys in Boiling HCl Solutions

	Corrosion Rate — mm/y		
Wt.% HCl	*Ti-Pd*	*625*	*C-276*
2.0	0.05	11.5	0.96
3.0	0.07	17.5	1.65
4.0	0.12	20.7	2.21

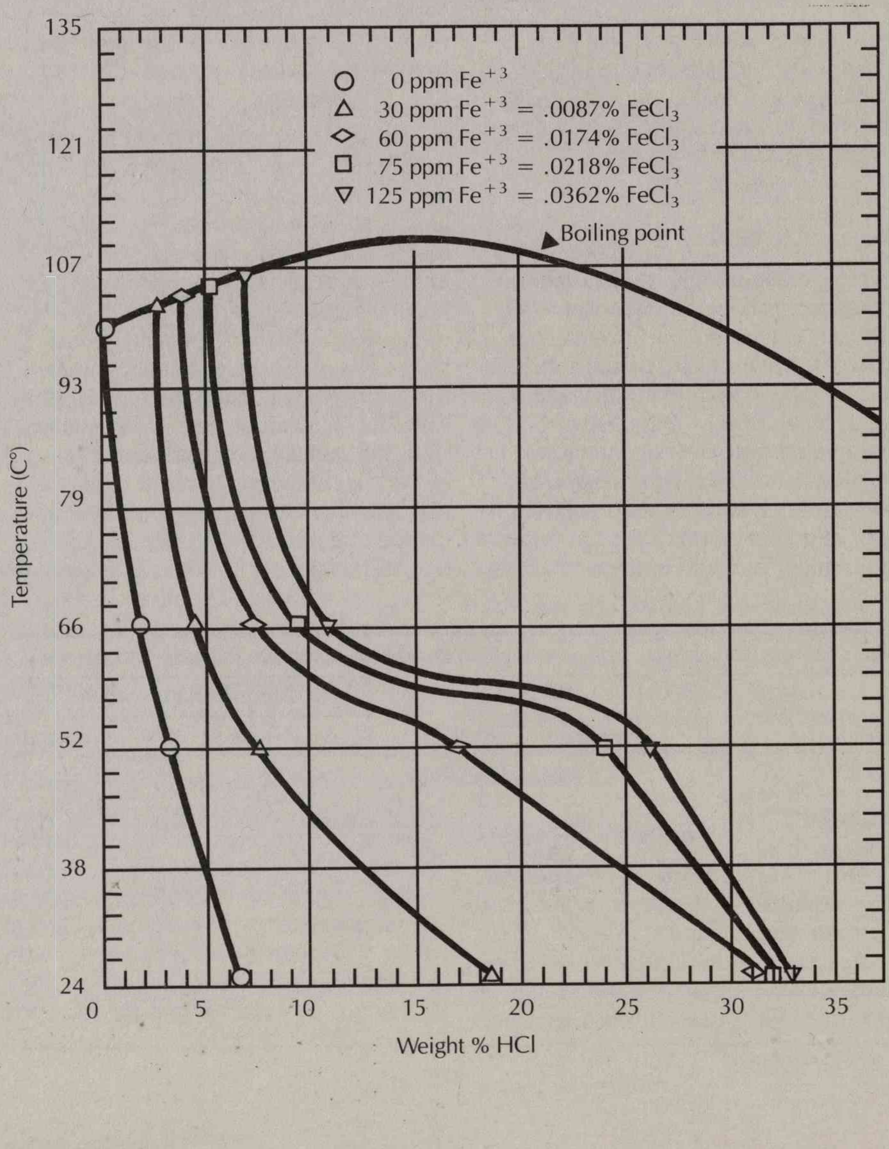
Passivation with Inhibitors Many industrial acid streams contain normal constituents or contaminants (i.e. up-stream corrosion products) which are oxidizing in nature, thereby passivating titanium alloys in normally aggressive acid media. Metal ion concentration levels as low as 20-100 ppm can provide extremely effective inhibition.

Common potent inhibitors for titanium in reducing acid media include dissolved oxygen, chlorine, bromine, nitrate, chromate, permanganate, molybdate and cationic metallic ions, such as ferric (Fe^{+3}), cupric (Cu^{+2}), nickelous (Ni^{+2}) and many precious metal ions. Figure 2 shows how the useful corrosion resistance of unalloyed titanium is significantly extended as the ferric ion concentration is increased in very small amounts. It is this potent metal ion inhibition phenomenon which permits titanium to be successfully utilized for equipment handling hot HCl and H_2SO_4 acid solutions in metallic ore leaching processes.

Although inhibition is possible in most reducing acids, protection of titanium from hydrofluoric acid solutions is extremely difficult to achieve. Hydrofluoric acid will generally cause rapid general corrosion of all titanium alloys, and should, therefore, be avoided.

Since the presence of minute quantities of these common inhibitive species can radically influence titanium's performance in reducing acids, one must consider all details of environment chemistry in the alloy selection process. Background process stream species are frequently beneficial for titanium. In addition, intentional addition of inhibitive species to the process stream can be a practical approach for extending titanium's corrosion resistance under marginal conditions.

Figure 2: Beneficial effect of minute ferric ion additions to corrosion resistance of unalloyed titanium in HCl media.



Alkaline Media Titanium is generally highly resistant to alkaline media including solutions of sodium hydroxide, potassium hydroxide, calcium hydroxide, magnesium hydroxide and ammonia hydroxide. In the highly basic sodium or potassium hydroxide solutions, however, useful application of titanium may be limited to temperatures below 176°F. (80°C.). This is due to possible excessive hydrogen uptake and eventual embrittlement of titanium alloys in hot, strongly alkaline media.

Titanium often becomes the material of choice for alkaline media containing chlorides and/or oxidizing chloride species. Even at higher temperatures, titanium resists pitting, stress corrosion, or the conventional caustic embrittlement observed on many stainless steel alloys in these situations.

Organic Chemicals

Titanium alloys generally exhibit excellent resistance to organic media. Mere traces of moisture and/or air normally present in organic process streams assure the development of a stable protective oxide film on titanium.

Titanium is highly resistant to hydrocarbons, chloro-hydrocarbons, fluorocarbons, ketones, aldehydes, ethers, esters, amines, alcohols and most organic acids. Anhydrous methanol is unique in its ability to cause stress corrosion cracking of titanium alloys. However, addition of more than 1.5% water is sufficient to eliminate this problem.

Titanium equipment has traditionally been used for production of terepthalic acid, adipic acid and acetaldehyde. Acetic acid, tartaric acid, stearic acid, lactic acid, tannic acids and many other organic acids represent fairly benign environments for titanium. However, proper titanium alloy selection is necessary for the stronger organic acids such as oxalic acid, formic acid, sulfamic acid and trichloroacetic acids. Performance in these acids depends on acid concentration, temperature, degree of aeration and possible inhibitors present. The grade 7 and 12 titanium alloys are often preferred materials in these aggressive acids.

Resistance to Gases

Oxygen and Air Titanium has excellent resistance to gaseous oxygen and air at temperatures up to 700°F. (370°C.). Above this temperature and below 840°F. (450°C.), titanium may form colored surface oxide films which may thicken slowly with time. Above 1000°F. (545°C.) or so, titanium alloys lack long-term oxidation resistance and will become brittle due to the increased diffusion of oxygen into the metal.

Titanium alloys are totally resistant to all forms of atmospheric corrosion regardless of pollutants present in either marine, rural or industrial locations.

Nitrogen and Ammonia Nitrogen reacts much more slowly with titanium than oxygen. However, above 1400°F. (800°C.), excessive diffusion of the nitride may cause metal embrittlement. Titanium is not corroded by liquid anhydrous ammonia at ambient temperatures. Moist or dry ammonia gas, or ammonia-water (NH_4OH) solutions will not corrode titanium to their boiling point and above.

Hydrogen The surface oxide film on titanium acts as a highly effective barrier to hydrogen penetration which can only occur when this protective film is disrupted mechanically or broken-down chemically or electro-chemically. The presence of moisture effectively maintains the oxide film inhibiting hydrogen absorption up to fairly high temperatures and pressures. On the other hand, pure, anhydrous hydrogen exposures should be avoided particularly as pressures and/or temperatures increase.

Excessive absorption of hydrogen in titanium alloys leads to embrittlement if a significant quantity of the brittle titanium hydride phase precipitates in the metal. Generally, hydrogen contents of at least several hundred ppm are required to observe significant embrittlement.

The few cases of hydrogen embrittlement of titanium observed in industrial service have generally been limited to situations involving high temperature, highly alkaline media; titanium coupled to active steel in hot aqueous sulfide streams; and where titanium has experienced severe very prolonged cathodic charging in seawater.

Sulfur-Bearing Gases Titanium is highly corrosion resistant to sulfur-bearing gases, resisting sulfide stress corrosion cracking and sulfidation at typical operating temperatures. Sulfur dioxide and hydrogen sulfide, either wet or dry, have no effect on titanium as shown in Table 4. Extremely good performance can be expected in sulfurous acid even at the boiling point. Field exposures in FGD scrubber systems of coal-fired power plants have similarly indicated outstanding performance of titanium (see Table 5).

Table 4: Corrosion of Unalloyed Titanium by Sulfur-Containing Gases

Gas	*Temp.*	*Corrosion Rate*
	(°C)	*(mm/y)*
SO_2 (Dry)	21-100	0.00
SO_2 (Water-Saturated)	21-100	<0.003
H_2S (Water-Saturated)	21-100	<0.12

Table 5: Comparative Alloy Corrosion Performance After 9 Months Exposure in the Outlet Duct Reheat Zone of a Closed-Loop FGD Scrubber

Alloy	*Specimen Type*	*Weight Loss**	*Maximum Pit Depth*
		(mg)	*(mm)*
Gr. 2 Ti	Base	0	0.00
Gr. 2 Ti	Welded	0	0.00
Gr. 12 Ti	Base	0	0.00
Gr. 12 Ti	Welded	0	0.00
C-276	Base	76	0.1
C-276	Welded	86	0.08
625	Base	374	1.78
625	Welded	557	0.74
904L SS	Base	2708	Perforated*
904L SS	Welded	2844	Perforated*

*Test Coupon Size was 50.8mm × 50.8mm × 3.2mm

Wet SO_3 environments may be a problem for titanium in cases where pure, strong, uninhibited sulfuric acid solutions may form, leading to metal attack. In these situations, the background chemistry of the process environment is critical for successful use of titanium.

Corrosion Resistance of High Strength Titanium Alloys

Most of the higher strength titanium alloys will exhibit excellent resistance to general corrosion and pitting corrosion in near-neutral environments which are neither highly oxidizing nor highly reducing. The metallurgical condition of the alloy plays a relatively minor role in corrosion performance, since oxide film stability is assured in these situations. When severe crevices exist in hot aqueous chloride media, most high strength titanium alloys will exhibit slightly reduced crevice corrosion resistance compared to unalloyed titanium. The titanium alloys rich in molybdenum, however, exhibit excellent resistance to this form of attack. It is for this reason, along with its favorable strength and low density, the high molybdenum 3Al-8V-6Cr-4Zr-4Mo alloy is a prime candidate for high temperature sour oil well and geothermal brine well production tubulars and other downhole components.

General corrosion resistance of high strength titanium alloys in strongly oxidizing or strongly reducing environments may diminish as aluminum and/or vanadium alloy content increases. Improvements in resistance to hot reducing acids can be achieved by increased alloy molybdenum content. The effects of various alloying elements on titanium alloy corrosion have been studied which indicate that suitable high strength alloys can be selected for a wide range of aggressive environments.

Another major consideration is resistance to stress corrosion cracking (SCC). Although the common industrial grades of titanium are generally immune to chloride SCC, certain high strength alloys may exhibit reduced toughness (K_{Ic}) values and/or accelerated crack growth rates in halide environments. Most of these alloys will not exhibit any susceptibility to SCC in smooth or notched conditions. However, above 480°F. (250°C.), resistance to hot salt SCC should be considered if chlorinated solvents, chloride salts, or other chlorine-containing compounds contact component surfaces.

High strength titanium alloys can successfully avoid SCC-related effects by consideration of alloy chemistry and/or preferred alloy heat treatments and microstructures. Selection of extra low interstitial (ELI) grades or alloys with transformed beta microstructures may offer significantly improved alloy toughness and resistance to SCC.

In summary, although high strength titanium alloys possess corrosion resistance which is generally superior to that of most common engineering alloys, consideration should be given to selecting a titanium alloy with full compatibility to a given environment. With the wide family of titanium alloys commercially available today, optimum high strength titanium alloy selection is almost always possible for a given environment. Technical consultation is available to assist the designer/user in achieving this end.

Erosion Resistance

Titanium's oxide film generally provides super resistance to abrasion, erosion, or erosion-corrosion in high velocity process streams. Some comparative alloy data is presented in Table 1, revealing titanium's superior performance to copper and aluminum alloys in flowing seawater. Even in heavy sand-laden seawater, insignificant metal loss was noted up to 18 ft/sec (5/5 m/sec).

Therefore, in contrast to copper alloys, titanium piping, equipment and heat exchangers can be designed for high flow velocities with little or no detrimental effects from turbulence, impingement or cavitation. This has positive implications relative to optimizing heat transfer efficiency, minimizing equipment wall thicknesses, minimizing tube and piping size and wall requirements, improving equipment reliability and reducing life cycle costs. It is for these reasons that titanium alloys, in either wrought or cast form, have become prime materials for various coastal chemical and power plants and marine/naval applications.

Heat Transfer

Titanium is a choice heat transfer material for shell/tube and plate/frame heat exchangers and many other types of heaters and coolers. In addition to excellent corrosion resistance, several other beneficial attributes of titanium interact to optimize exchanger heat transfer efficiency:

- ☐ Good strength
- ☐ Resistance to erosion and erosion-corrosion
- ☐ Very thin, conductive oxide surface film
- ☐ Hard, smooth, difficult to adhere to surface
- ☐ Surface promotes dropwise condensation

Based on its excellent resistance to corrosion and erosion-corrosion, titanium can be designed with a zero corrosion allowance which, with its good strength, permits use of very thin heat transfer walls. Furthermore, very high fluid flow rates can be designed for titanium exchangers reflecting its outstanding resistance to fluid erosion, cavitation and impingement. These higher flow rates directly increase overall heat transfer efficiency, while improving surface cleanliness.

This reduces exchanger size and material requirements and minimizes the total cost of titanium exchangers. In fact, titanium can be comparable in initial cost to certain copper or stainless steel alloys when full advantage is taken of titanium's unique properties.

The use of thinner titanium heat transfer wall thicknesses tends to offset titanium's somewhat lower thermal conductivity. However, it is the surface characteristics of titanium that offer the greatest benefit to heat transfer. The limiting factor in heat transfer is the insulating metal-fluid interface films which often form in service. The high resistance of titanium to corrosion prevents buildup of corrosion products which rob metals of heat transfer efficiency.

Titanium's hard, smooth surface also minimizes adherence and buildup of external fouling films, making cleaning and maintenance easier. It is not unusual to observe a 95-100% cleanliness factor for titanium in many services. Although titanium is not biotoxic, successful control of biofouling is achievable by periodic chlorination and/or mechanical means (tube brushes, sponge balls). A fouling factor of 0.0005 is easily achieved for titanium in seawater using these strategies. Although the copper alloys possess higher metal thermal conductivity and higher overall heat transfer coefficients when new and clean, titanium exhibits the higher long-term operating coefficients in actual service (Figure 3.)

Titanium is also unique in its ability to promote dropwise condensation on its surface. When condensing water vapor from evaporative processes, most metals form continuous surface films of condensate. This mechanism of condensation is not nearly as efficient as titanium's dropwise mechanism as shown in Figure 4 , for brine and nitric acid distillation examples.

Putting it all together—taking full advantage of all of titanium's beneficial properties to optimize heat transfer leads to extremely reliable, highly efficient, cost competitive heat exchangers. Not only will initial exchanger costs for titanium be highly attractive relative to the more common engineering alloys, but improvements in life cycle cost in aggressive service resulting from reduced maintenance/cleaning requirements will also be evident. Titanium is readily available in welded and seamless tubing in many alloy grades for tubular exchangers,

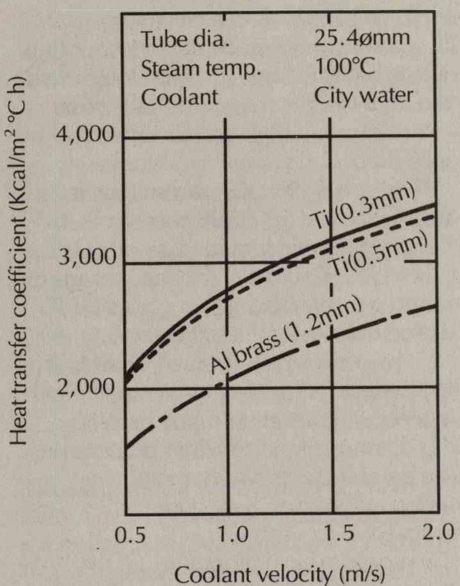
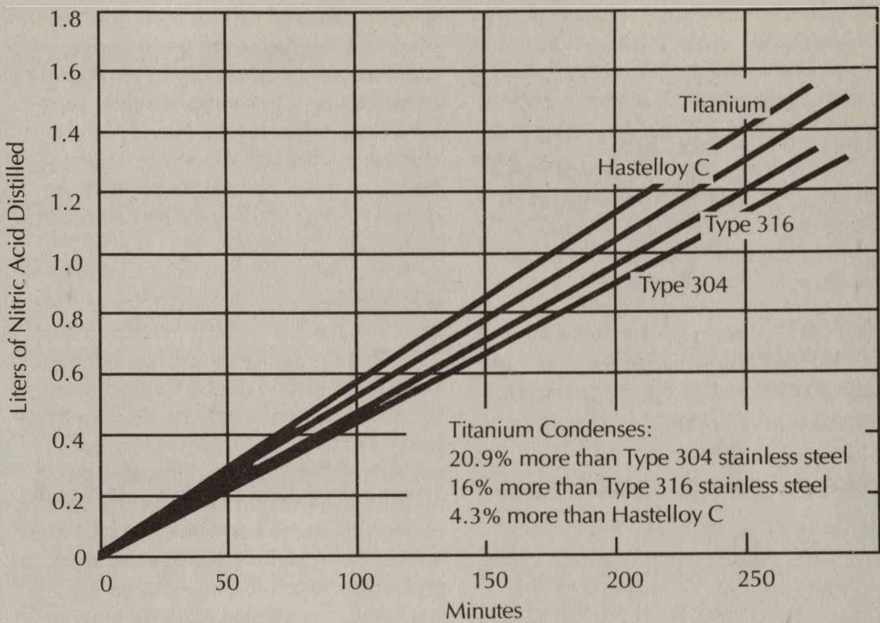
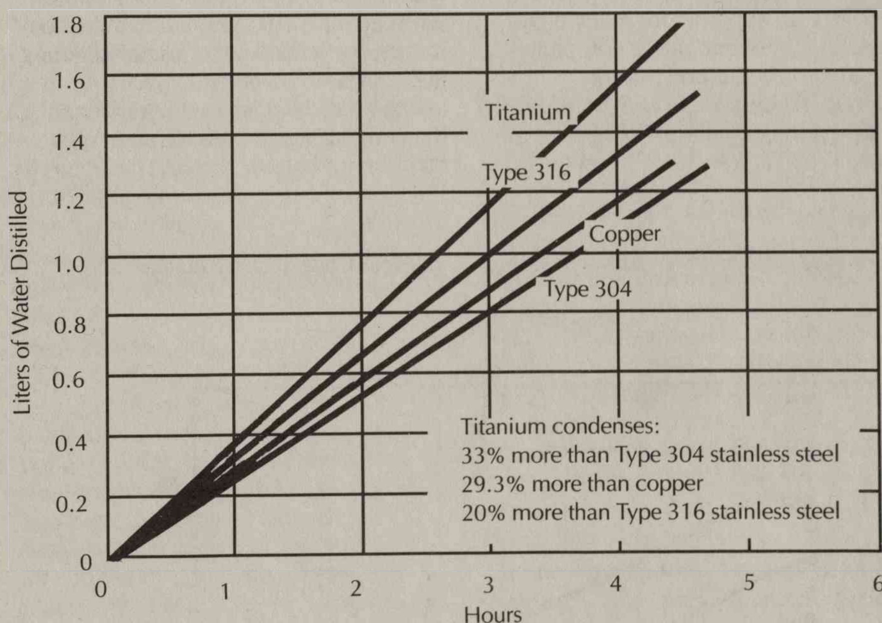


Figure 3: Heat transfer rate of the tubes used in a model condenser for six months*



Relative rates of nitric acid distillation from a 70% nitric acid solution.



Relative rates of water distilled from a 3.5% sodium chloride solution.

Figure 4: Rates of distillation and condensation are high for titanium compared to other metal heat exchanger surfaces.

or in pressed plate form for plate and frame exchangers.

Strength and Other Mechanical Properties

The family of titanium alloys offer a full range of strength properties spanning from the highly formable, lower strength to the very high strength alloys. Most of the alpha-beta and beta alloys can provide a myriad of strength-ductility property combinations through adjustments in alloy heat treatment and/or composition. Thus, a suitable titanium alloy can always be selected for specific application needs.

One of the most attractive characteristics of the titanium alloys is their outstanding strength to weight ratio compared to many other engineering metals. This means increased structural efficiency in design, manifesting itself as weight, space or cost reduction depending on the application. High strength to density has been the traditional driving force for the extensive utilization of titanium alloys in a multitude of aerospace applications. Many innovative applications outside the realm of aerospace have developed over the years based on strength to weight requirements, often combined with the excellent corrosion resistance that titanium offers. Examples include deep sea submersible hulls and ballast tanks, and deep well (downhole) tubulars and logging tools.

Titanium alloys also offer a wide range of fatigue, creep and toughness properties to temperatures as high as 1000°F. (540°C.). Appendix I lists several relevant mechanical properties for the family of titanium alloys available.

Many titanium alloys have been approved for pressurized equipment falling under the ASME Boiler and Pressure Vessel Code. Figure 5 presents the maximum design allowable stresses for titanium alloys under this code. Compared to these ASME code approved titanium alloys, Ti-3Al-2.5V can offer significantly higher design allowables for pressure vessels. The Titanium Development Association is currently sponsoring a program to provide the necessary

*This figure is from "Thinner Wall Welded Titanium Tubes for Seawater Desalination Plants," page 39. Courtesy of the Japan Titanium Society.

data to obtain ASME code approval of Ti-3Al-2.5V.

Physical Properties

Titanium and its alloys possess many unique physical properties which make them ideal for equipment design, even when strength or corrosion resistance may not be critical. These unique properties include:

- Low Density
- Low Modulus of Elasticity
- Low Coefficient of Expansion
- High Melting Point
- Non-Magnetic
- Extremely Short Radioactive Half-Life

Titanium's low density, roughly 56% that of steel, means twice as much metal volume per pound. Particularly when combined with alloy strength, this often means smaller and/or lighter components. Although obviously the basis for aerospace applications, positive implications are also apparent for many types of rotating or reciprocating components such as centrifuges and pumps.

Reduced component weight is also of interest in certain aggressive environments. For example, downhole oil and geothermal well production tubulars and logging tools are being produced from titanium alloys based on these property combinations. In marine service, pleasure boat components, Naval surface ships and submarine cooling water systems are growing markets for titanium driven by its immunity to seawater corrosion and light weight.

Titanium alloys exhibit modulus of elasticity values which are approximately 50% of steel. This low modulus means excellent flexibility which has been the basis for its use in dental fixtures (braces, etc.) and human prosthetic devices (hip joints, bone implants, etc.). Titanium's excellent compatability provides an additional incentive for titanium's rapidly expanding use in body prosthetics. Other applications include springs, bellows, golf club shafts and tennis racquets.

Titanium possesses a coefficient of expansion which is significantly less than ferrous alloys. This property also allows titanium to be much more compatible with ceramic or glass materials than most metals, particularly when metal-ceramic/glass seals are involved.

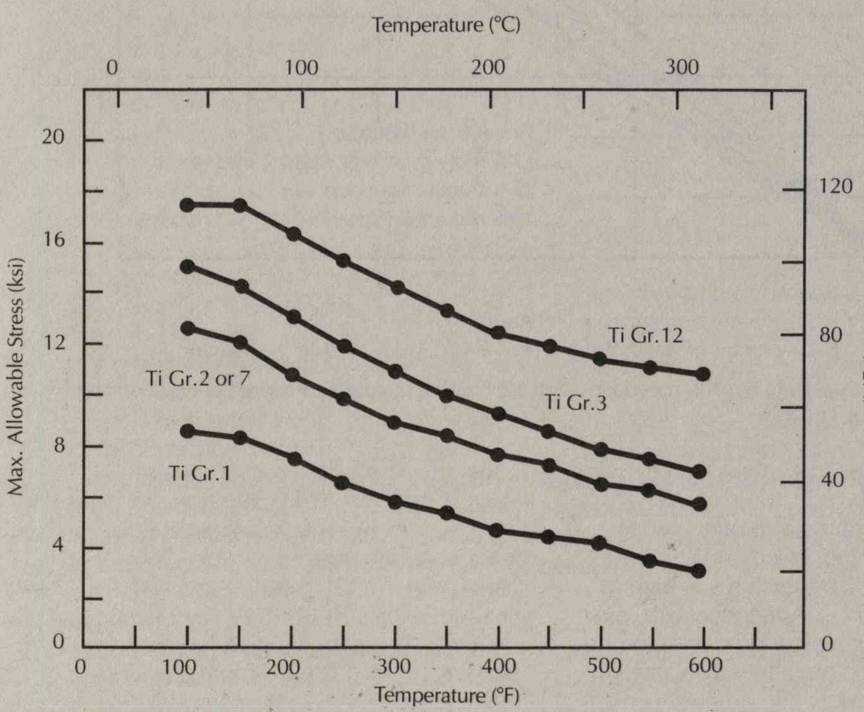
The relatively high melting point of titanium has led to consideration of titanium for ballistic armor. The higher melting point tends to reduce susceptibility to armor melting and ignition (burning) during ballistic impact. Good toughness and light weight are additional factors for considering titanium alloys in this application.

Titanium is virtually non-magnetic, making it ideal for applications where electro-magnetic interference must be minimized. Desirable applications include electronic equipment housing and downhole well logging tools.

Titanium has an extremely short half-life, thereby permitting its use in nuclear systems. In contrast to many ferrous alloys, many titanium alloys do not contain a significant amount of alloying elements which may become radioactive.

Typical physical properties for the family of titanium alloys are presented in Appendix I.

Figure 5: Maximum design allowable in tension for ASME Code-qualified titanium alloys.



Fabrications

The technology of fabricating titanium has evolved from simple conventional processes to highly sophisticated techniques. A wide range of capabilities are now available. End application specifications and economics should determine the process selected. In order to optimize fabrication, considerations must be given to the grade or alloy, heat treatment and crystal structure.

Although titanium is readily fabricable, some general differences from other structural metals should be recognized: lower modulus of elasticity, higher melting point, lower ductility, propensity to gall and sensitivity to contamination in air at welding temperatures.

Titanium can usually be cold worked on equipment designed for stainless steel. Press brakes used for forming sheet, shears, cold rolls, hydro press forming, drawing and pilgering can all be used. The majority of aircraft and some industrial components require hot working to overcome springback, minimize stresses and to reduce the high forming forces needed for titanium alloys.

Casting, forging, hot forming and other elevated temperature processes, play an important roll in providing shapes with desired properties and maximum metal utilization. Forgings are the workhorse of the aerospace industry with a wide range of sizes available. New developments in precision forgings now provide near net shapes with improved material efficiencies. Both investment and sand or graphite mold castings are used and have increased significantly with the use of hot isostatic pressing (HIP'ing) to seal internal voids and improve properties. Extrusions and hot rolling are used to produce shapes. Hot forming of sheet and plate is extensively used for aircraft components. Superplastic forming under pressure and temperature has recently found growing acceptance. Diffusion bonding is often incorporated in the same process.

Welding requires adherence to rules of cleanliness and exclusion of reactive gases including air. Welding by means of the TIG process (Tungsten Electrode Inert Gas) using argon gas shielding is most commonly used. Plasma, laser, resistance, electron beam, MIG, and welding friction all have their place. Techniques are available to weld titanium under a wide range of conditions both in the shop and in the field.

Cladding is being performed by a range of processes primarily for industrial equipment. Explosive bonding and mechanical fastened loose lining have been used for years. More recently roll cladding, resistance weld lining and diffusion bonding are being applied.

Machining by all of the customary methods is being done. Some preferred procedures are recommended such as sharp tools, rigid set-ups, heavy feeds, slow speeds and an abundance of soluble coolant. Work hardening rate is less than that for stainless steels. Drilling and cold saw cutting require sharp, clean tools with good chip removal and ample coolant.

Torchcutting with oxyacetylene flame can be accomplished in sections up to 6" thick. Care must be taken to remove all surface contaminant. Hard wheel abrasive grinding, using clean wheels with large grains can be used to clean cut edges without alpha phase contamination as excessive heat build-up is avoided.

Applications

Titanium and its alloys have proven to be technically superior and cost-effective materials of construction for a wide variety of aerospace, industrial, marine and commercial applications. In North America, approximately 70% of the titanium consumed is utilized for aerospace applications. Due to the expansion of existing applications and the development of new uses, the greatest growth will occur in the industrial, marine and commercial sectors.

Industrial applications in which titanium-based alloys are currently utilized include:

Gas Turbine Engines Highly efficient gas turbine engines are possible only through the use of titanium-based alloys in components like fan blades, compressor blades, discs, hubs and numerous non-rotor parts. The key advantages of titanium-based alloys in this application include high strength/weight ratio, strength at moderate temperatures and good resistance to creep and fatigue. The development of titanium aluminides (see page 11) will allow the use of titanium in hotter sections of a new generation of engines.

Heat Transfer The major industrial application for titanium remains in heat transfer applications in which the cooling medium is seawater, brackish water or polluted water. Titanium condensers, shell and tube heat exchangers, and plate and frame heat exchangers are used extensively in power plants, refineries, air conditioning systems, chemical plants, offshore platforms, surface ships and submarines. The life span and dependability of titanium are demonstrated by the fact that of the millions of feet of welded titanium tubing in power plant condenser service, there have been no reported failures due to corrosion on the cooling water side.

DSA-dimensional stable anodes The unique electrochemical properties of the titanium DSA make it the most energy efficient unit for the production of chlorine, chlorate and hypochlorite.

Pulp and Paper Due to recycling of waste fluids and the need for greater equipment reliability and life span, titanium has become the standard material for drum washers, diffusion bleach washers, pumps, piping systems and heat exchangers in the bleaching section of pulp and paper plants. This is particularly true for the equipment developed for chloride dioxide bleaching systems.

Desalination Excellent resistance to corrosion, erosion, and high condensation efficiency, make titanium the most cost-effective and dependable material for critical segments of desalination plants. Increased usage of very thin walled welded tubing makes titanium competitive with copper-nickel.

Extraction and Electrowinning of Metals Hydrometallurgical extraction of metals from ores in titanium reactors is an environmentally safe alternative to smelting processes. Extended lifespan, increased energy efficiency and greater product purity are factors promoting the usage of titanium electrodes in electro-winning and electro-refining of metals like copper, gold, manganese and manganese dioxide.

Medical Titanium is widely used for implants, surgical devices, pacemaker cases and centrifuges. Titanium is the most bio-compatible of all metals due to its total resistance to attack by body fluids, high strength and low modulus.

Hydrocarbon Processing The need for longer equipment life, coupled with requirements for less downtime and maintenance, favor the use of titanium in heat exchangers, vessels, columns and piping systems in refineries, LNG plants and offshore platforms. Titanium is immune to general attack and stress corrosion cracking by hydrocarbons, H_2S, brines and CO_2.

Marine Applications Because of high toughness, high strength and exceptional erosion/corrosion resistance, titanium is currently being used for submarine ball valves, fire pumps, heat exchangers, castings, hull material for deep sea submersibles, water jet propulsion systems, shipboard cooling and piping systems.

Chemical Processing Titanium vessels, heat exchangers, tanks, agitators, coolers, and piping systems are utilized in the processing of aggressive compounds, like nitric acid, organic acids, chlorine dioxide, inhibited reducing acids and hydrogen sulfide.

Steam Turbines Over 30% of the downtime of powerplants is caused by failures of steam turbine components. The use of Ti-6Al-4V turbine blades in the Wilson Line region increased the efficiency and life of the low pressure steam turbine while decreasing downtime and maintenance.

Automotive Titanium is already extensively utilized in high performance vehicle components such as valves, valve springs, rocker arms, connecting rods and frames due to its high strength and low weight. Evaluations have demonstrated that use of a titanium valve train improves fuel efficiency by 4% in commercial engines. Because of this factor, titanium valve train components are being evaluated in several commercial engines.

Castings Commercial casting production started in the late 1960s and today the technology has matured to the point where critical gas turbine engine, air frame, chemical process and marine products are routinely supplied. Castings are the most commercially advanced and diversified of the net shape technologies available to the user. They offer greater design freedom and greatly reduce the need for expensive metal removal or fabrication to attain the desired shape.

Both precision lost wax as well as rammed graphite (sand) molding systems are employed. The same pattern equipment normally used to produce steel parts is often used to produce titanium chemical pump and valve components while aerospace parts normally require their own tooling.

Mechanical properties of titanium castings are generally comparable to their wrought counterparts. Toughness and crack growth resistance are generally superior and strength is almost the same while high cycle fatigue is normally a little lower.

The introduction of hot isostatic pressing (HIP) in the late 1970s tumbled the barriers associated with X-ray interpretation of normal internal casting shrinkage cavities since such indications were closed and diffusion bonded by the process. By the elimination of typical internal microshrink, mechanical property scatter was reduced and average property levels improved. As designers began to have greater confidence, applications increased dramatically.

Sports Equipment Titanium golf shafts, tennis racquet frames, pool cue shafts, ball bats and bicycle frames are currently being fabricated using the Ti-3Al-2.5V alloy. Ti-3Al-2.5V has demonstrated the properties needed for sports applications: good strength-to-weight ratio, good corrosion resistance, low modulus of elasticity, and dampening characteristics.

In the aerospace industry, titanium is currently being utilized in:

Engines The largest single use of titanium is in the aircraft gas turbine engine. In most modern jet engines, titanium-based alloy parts make up 20% to 30% of the dry weight, primarily in the compressor. Applications include blades, discs or hubs, inlet guide vanes and cases. Titanium is most commonly the material of choice for engine parts that operate up to 1100°F. (593°C.).

Airframes Titanium alloys effectively compete with aluminum, nickel and ferrous alloys in both commercial and military airframes. For example, the all-titanium SR 71 still holds all speed and altitude records. Applications run the gamut of airframe structural members; from massive, highly stressed, forged wing structures, and landing gear components, to small critical fasteners, springs, and hydraulic tubing.

Selection of titanium in both airframes and engines is based upon titanium's basic attributes; weight reduction due to high strength to weight ratios coupled with exemplary reliability in service, attributable to outstanding corrosion resistance compared to alternate structural metals.

Space Structures Starting with the extensive use of titanium in the early Mercury and Apollo space craft, titanium alloys continue to be widely used in military and NASA space applications. In addition to manned space craft, titanium alloys are extensively employed in solid rocket booster cases, guidance control pressure vessels and a wide variety of applications demanding light weight and reliability.

Thick Section Titanium Heavy section size is generally defined as forged or rolled thickness that exceeds four inches. Titanium alloys have been successfully used for heavy sections thickness, in both airframe parts, and in rotating components such as heavy section fan disks for PWA and G.E. high bypass jet engines, and Sikorsky helicopter rotor forgings.

The primary alloys that have been involved are Ti-6Al-4V, in the annealed or STOA (Solution Treated and Overaged) condition; the near-beta Ti-17 (Ti-5Al-2Sn-2Zr-4Mo-4Cr), Ti-10V-2Fe-3Al and the Ti-6Al-2Sn-4Zr-6Mo compositions in the STA (Solution Treated Aged) condition; and the beta alloys Ti-13V-11Cr-3Al and Ti-3Al-8V-6Cr-4Mo-4Zr, also in the STA condition. Certainly the most extensive heavy section applications in one project to date featured the Ti-13V-11Cr-3Al alloy in the SR-71 Blackbird (fuselage frames, wing beams and landing gears). In this program, Lockheed engineers stated that while only titanium and steel had the ability to withstand the operating temperatures encountered, aged Ti-13V-11Cr-3Al titanium weighed one-half as much as stainless steel per cubic inch and it's ultimate strength was about equal to stainless. Using "conventional" fabrication techniques, fewer parts were needed with Ti-13V-11Cr-3Al than with steel.

For a given process and heat treatment condition, titanium alloys such as these demonstrate superior fatigue and fracture toughness properties, not only in the absolute sense, but also from the standpoint of uniformity throughout the heavy section thickness, and as the section thickness increases from 4" to 6", or even to 8". Titanium alloys offer a useful and in many cases, a superior alternative to steel alloys for heavy section application.

Emerging Applications

Besides existing applications, there is tremendous potential for titanium usage which include the following:

Aerospace As new titanium products, alloys and manufacturing methods are employed by the aerospace industry, the use of titanium will expand. Today the use of precision castings and new alloys such as Ti-15V-3Cr-3Al-3Sn and Ti-3Al-8V-6Cr-4Zr-4Mo are making it possible for titanium to displace alternate, less efficient structural materials in a wide spectrum of aerospace applications.

Downhole The exceptional resistance to attack from H_2S and other aggressive compounds combined with high strength and low density make titanium especially attractive for downhole applications such as packers, tube strings, stress riser joints, safety valves and springs.

FGD (Flue Gas Desulfurization) Laboratory and field studies have proven titanium to have exceptional corrosion/erosion resistance to FGD systems. Its long life makes titanium a prime candidate for pollution control systems.

Food and Pharmaceutical Titanium demonstrates excellent corrosion resistance, not only to various food products and pharmaceutical chemicals, but also to the cleaning agents utilized. As equipment life becomes a more critical factor in financial evaluations, titanium equipment may begin to replace existing stainless steel apparatus.

Nuclear Waste Storage Nuclear waste must be stored safely for hundreds of thousands of years. Titanium's proven resistance to attack from naturally occurring fluids makes it a prime candidate for multi-barrier disposal systems.

Commercial Applications Titanium's unique blend of properties make it a natural choice for various types of commercial uses, including jewelry, roofs, horseshoes, pens, watches, golf club shafts, BMX bikes, tennis racquets, eyeglass frames and hand tools.

Marine The optimal erosion/corrosion resistance properties of titanium make it the metal of choice for any fluid flow component. Potential applications include submarine hulls, submarine condensers, ship superstructures, weapons systems, seawater piping systems, exhaust uptakes, vertical launch systems, hangar bay doors, jet blast deflectors and ventilation ducting.

Metal Matrix Composites Titanium is becoming a select material as a matrix in the emerging development of metal matrix composites for aerospace as well as industrial applications. While offering a high temperature resistant ductile base, titanium can be further strengthened and stiffened with the addition of ceramic or intermetallic compounds in fiber or particulate form to produce properties beyond those achieved by alloying alone.

Current developments using SiC and TiC reinforcements will permit titanium base composites to replace nickel and steel alloys in higher temperature and higher modulus applications.

Titanium Aluminides This class of materials, typically containing 15-35% Al, represents the next generation of alloys intended to push the applications of titanium beyond the traditional 1000°F. barrier. Two types of aluminides currently are under investigation. The class known as alpha 2 is typified by the Ti_3Al intermetallic compound; whereas, the gamma aluminides are represented by the Ti-Al formula. Variations of both types, containing a variety of alloying elements, are being studied to overcome the inherent low ductility of these compounds. Currently, two application areas are the focus of attention. The National Aerospace Plan provides the main impetus for development activity, both for the airframe and the hypersonic engines. The Integrated High Performance Turbine Engine Technology program, paving the way for future generations of aircraft gas turbine engines, will also utilize these materials to achieve their intended performance goals. Thus, the high mach-number aerospace vehicles and propulsion systems designed to usher in the age of hypersonic flight will become a reality with these materials.

Architectural Titanium reinforcement rods are being used in the restoration of antiquities such as the Parthenon and to repair concrete bridge structures. In Japan, commercially pure titanium is being used for roofing, window frames, eaves and gables, flashing wall curtains, railings, ventilators, and interior and exterior appendages. In the United States, titanium is bonded to glass for exterior use in buildings.

Appendix 1: Properties of Titanium Grades

		Commercially Pure	Commercially Pure	Commercially Pure	Commercially Pure
Designation		**Grade 1**	**Grade 2**	**Grade 3**	**Grade 4**
Chemical Composition (percent)	(Max. values unless range is shown)	0.08 C; 0.20 Fe; 0.03 N; 0.18 O; 0.015 H(sheet) 0.0125 H (bar) 0.0100 H (billet)	0.10 C; 0.30 Fe; 0.03 N; 0.25 O; 0.015 H (sheet) 0.0125 H (bar) 0.0100 H (billet)	0.10 C; 0.30 Fe; 0.05 N; 0.35 O; 0.015 H (sheet) 0.0125 H (bar) 0.0100 H (billet)	0.10 C; 0.50 Fe; 0.05 N; 0.40 O; 0.015 H (sheet) 0.0125 H (bar) 0.0100 H (billet)
Mill Annealed Tensile Properties		**Guar.R.T. Min.**	**Guar.R.T. Min.**	**Guar.R.T. Min.**	**Guar.R.T. Min.**
Ultimate Strength (psi)		35,000	50,000	65,000	80,000
Yield Strength (psi) 0.2% offset		25,000	40,000	55,000	70,000
Elongation in 2" (%) Sheet>0.025 thick		24	20	18	15
Reduction in Area (%) Bar		30	30	30	25
Mechanical Properties (Typical)				800°F	800°F
Stress to Rupture in Time Shown	Stress (psi)			20,000	17,000
	Time (hrs.)			100	450
Stress and Time to Produce Elongation Shown (creep)	Stress (psi)				8,000
	Time (hrs.)				150
	Creep (%)				.15
Charpy V-Notch Impact (ft.-lbs.) @ Rm. Temp.			25-40	20-40	
Bend Radius	Under 0.070" thick	1.5 × Thickness	2.0 × Thickness	2.0 × Thickness	2.5 × Thickness
	0.070" and Over	2.0 × Thickness	2.5 × Thickness	2.5 × Thickness	3.0 × Thickness
Welded Bend Radius		1.5-2.0 × Thickness	2.0-3.0 × Thickness	2.0-3.0 × Thickness	3.0-5.0 × Thickness
Hardness		R_B70	R_B80	R_B90	R_B100
Physical Properties					
Beta Transus (F ± 25)		1630	1675	1690	1740
Coefficient of Thermal Expansion (10^{-6}in./in./F)	32-212	4.8	4.8	4.8	4.8
	32-600	5.1	5.1	5.1	5.1
	32-1000	5.4	5.4	5.4	5.4
	32-1200	5.6	5.6	5.6	5.6
	32-1500	5.6	5.6	5.6	5.6
Density (lbs./cu.in.)		0.163	0.163	0.163	0.163
Melting Point, Approx. (F)		3040	3020	3020	3020
Electrical Resistivity (@ R.T. (Microhms cm)		56	56	56	60
Modulus of Elasticity — Tension (10^6 psi)		14.9	14.9	15.0	15.1
Modulus of Elasticity — Torsion (10^6 psi)		6.5	6.5	6.5	6.5
Thermal Conductivity (Btu/hr./sq.ft./F/Ft.)		9.0 @ Rm. Temp.	9.5 @ Rm. Temp.	9.5 @ Rm. Temp.	9.8 @ Rm. Temp.
Specific Heat (Btu/Lb./F) @ Rm. Temp.		0.124	0.124	0.125	0.129
Weldability		GOOD	GOOD	GOOD	GOOD
Annealing Temp. (F)	Full	1300/30 Min.-2 Hrs.; Air Cool	1300/30 Min.-2 Hrs.; Air Cool	1300/30 Min.-2 Hrs.; Air Cool	1300/30 Min.-2 Hrs.; Air Cool
	Stress Relief	1000-1100/30 Min.; Air Cool	1000-1100/30 Min.; Air Cool	1000-1100/30 Min.; Air Cool	1000-1100/30 Min.; Air Cool
Forging* Temp. (F)	Blocking	1600-1700	1600-1700	1600-1700	1650-1700
	Finishing	1500-1600	1500-1600	1500-1600	1500-1600
Available Mill Products		Bar; Billet; Extrusions; Plate; Sheet; Strip; Wire; Pipe; Tubing	Bar; Billet; Castings; Extrusions; Plate; Sheet; Strip; Wire; Pipe; Tubing	Bar; Billet; Castings; Extrusions; Plate; Sheet; Strip; Wire; Pipe; Tubing	Bar; Billet; Extrusions; Plate; Sheet; Strip; Wire; Pipe; Tubing
Typical Applications		For corrosion resistance in the chemical and marine industries, and where maximum ease of formability is desired.	For corrosion resistance in the chemical and marine industries, and where a higher strength level and ease of formability is desired.	For corrosion resistance in the chemical and marine industries.	For corrosion resistance in the chemical and marine industries.
Industry Specifications		ASTM B265 Gr 1 ASTM B348 Gr 1 ASTM B337 Gr 1 ASTM B338 Gr 1 ASTM B381 Gr 1 ASTM F67 Gr 1 ASTM F467 Gr 1 ASTM F468 Gr 1	AMS 4902 ASTM B265 Gr2 ASTM B337 Gr2 ASTM B338 Gr2 ASTM B348 Gr2 ASTM B367 Gr2 ASTM B381 Gr2 ASTM F67 Gr2 ASTM F467 Gr2 ASTM F468 Gr2	AMS 4900 ASTM B265 Gr3 ASTM B337 Gr3 ASTM B338 Gr3 ASTM B348 Gr3 ASTM B367 Gr3 ASTM B381 Gr3 ASTM F67 Gr3	AMS 4901; 4921 ASTM B348 Gr4 ASTM B381 Gr4 ASTM F67 Gr4 ASTM F467 Gr4 ASTM F468 Gr4

*Maximum Material Temperature in Furnace

Commercially Pure	Commercially Pure	Alpha Alloy		Alpha-Beta Alloy		Alpha-Beta Alloy		Alpha-Beta Alloy	
Grade 7	**Grade 12**	**Ti-5Al-2.5 Sn**		**Ti-6Al-4V**		**Ti-3Al-2.5V**		**Ti-6Al-2Sn-4Zr-2Mo**	
0.10 C; 0.30 Fe; 0.03 N; 0.12/ 0.25Pd; 0.25 O; 0.15H(sheet) 0.0125 H;(bar)	0.08 C; 0.03 N; 0.30 Fe; 0.015 H; 0.25 O; 0.2/0.4 Mo; 0.6/0.9 Ni	.08 C; .50 Fe; .05 N; .20 O_2 4.0/6.0 Al; 2.0/3.0 Sn H_2 .0200(forging, bar, sheet)		.08 C; 0.25 Fe; .05N 0.20 O;5.50/ 6.75 Al; 3.5/4.5 V; 0.0150 H(sheet) 0.0125 H(bar); 0.0100 H(billet)		0.05 C; 0.02 N; 0.30 Fe; 0.12 O; 2.5/3.5 Al; 2.0/3.0 V 0.0150 H(sheet); 0.0125 H(bar)		.10 C; .25 Fe; 0.5 N; .15 O_2; 5.5/6.5Al; 1.8/2.2 Sn; 3.6/4.4 Zr; 1.8/2.2Mo .06-.1Si; 0.125H_2(bar); 150H_2(forging)	
Guar.R.T. Min.	**Guar.R.T. Min.**	**Guar.R.T. Min.**		**Guar.R.T. Min.**		**Guar.R.T. Min.**		**Guar.R.T. Min.**	
						Mil Ann.	**C.W.S.R.****		
50,000	70,000	120,000		130,000		90,000	125,000	130,000	
40,000	50,000	115,000		120,000		75,000	105,000	120,000	
20	18	10		10		15	10	10	
25	25	25		25				25	
		800°F	1000°F	600°F	800°F	600°F		800°F	1000°F
		62,000	20,000	98,000	60,000	50,000			50,000
		1,000	1,000	1,000	1,000	100			50hrs.
		48,000	5,000	70,000	32,000			58,000	12,000
		100	100	1,000	1,000			1,000	1,000
		0.1	0.1	0.1	0.1			0.1	0.1
		10-15		10-14					
2.0 × thickness	2.0 × Thickness	4.0 × Thickness		4.5 × Thickness				4.5 × Thickness	
2.5 × Thickness	2.5 × Thickness	4.5 × Thickness		5.0 × Thickness				5.0 × Thickness	
2.0-3.0 × Thickness		5-6 × Thickness		6.0-10.0 × Thickness				5.0 × Thickness	
R_B80		R_C36		R_C36					
1675	1634	1900		1830		1715		1820	
4.8		5.2		5.0		5.3		4.3	
5.1	5.3	5.3		5.3		5.5		4.5	
5.4		5.3		5.6		5.5		4.5	
5.6		5.4		5.9					
5.6		5.6		6.1					
0.163	0.163	0.162		0.160		0.162		0.164	
3020	3020	2910		3200		3100		3100	
56	52	157		171		126		171	
14.9	15.0	16.0		16.5		15.0		16.5	
6.5	6.2	7.0		6.1					
9.5 @ Rm. Temp.	11.0 @ Rm. Temp.	4.5 @ Rm. Temp.		3.9 @ Rm. Temp.					
0.124	0.13	0.125		0.135					
GOOD	GOOD	GOOD		FAIR		GOOD		FAIR	
1300/30 Min.-2 Hrs.; Air Cool	1300/30 Min.-2 Hrs.; Air Cool	1325-1550/5 Min.-4 Hrs.; Air Cool		1300-1450/15 Min.-2 Hrs.; Air Cool		1200-1400/1 Hr.; Air Cool		Duplex-sheet 1650/30 Min.;*	
1000-1100/30 Min.; Air Cool	1000-1100/30 Min.; Air Cool	1000-1200/15 Min.-1 Hr. Air Cool		900-1200/1-4 Hrs.; Air Cool		1000-1200/1 Hr.; Air Cool		900-1200 1-4 Hrs. Air Cool	
1600-1700	1600-1700	1850-1950		1750-1800		1600-1650		1900-1950	
1500-1600	1500-1600	1800-1850		1650-1750		1550-1600		1750-1800	
Bar; Billet; Castings; Extrusions; Plate; Sheet; Strip; Wire; Pipe; Tubing	Bar; Billet; Castings; Extrusions; Plate; Sheet; Strip; Wire; Pipe; Tubing	Bar; Billet; Castings; Extrusions; Plate; Sheet; Wire;		Bar; Billet; Castings; Extrusions; Plate; Sheet; Strip; Wire		Bar; Tubing; Strip		Bar; Billet; Castings; Sheet; Strip; Wire	
For corrosion resistance in the chemical industry where media is midly reducing or varies between oxidizing and reducing.	For corrosion resistance in the chemical industry where media is midly reducing or varies between oxidizing and reducing.	Air frame and jet engine applications requiring good weldability, stability and strength at elevated temperatures.		Jet engine components; air frame forgings; sheet; plate; air frame components.		Air frames and jet engines; hydraulic and fuel lines.		For use where optimum creep strength and high strength at elevated temperature are required.	
ASTM B265 Gr 7 ASTM B337 Gr 7 ASTM B338 Gr 7 ASTM B348 Gr 7 ASTM B367 Gr 7 ASTM B381 Gr 7 ASTM F467 Gr 7 ASTM F468 Gr7	ASTM B265 Gr12 ASTM B348 Gr12 ASTM B337 Gr12 ASTM B338 Gr12 ASTM B381 Gr12 ASTM F467 Gr12 ASTM F468 Gr12	AMS 4910;4926;4966 ASTM B367 Gr6		AMS 4911;4928;4930;4931;4935; 4965;4967;4985;4991 ASTM B265 Gr5 ASTM B348 Gr5 ASTM B367 Gr5 ASTM B381 Gr5 ASTM F467 Gr5 ASTM F468 Gr5		AMS 4943;4944;4945 ASTM B337 Gr9 ASTM B338 Gr9 ASTM B381 Gr9		AMS 4919;4975;4976	

**Cold-Worked Stress Relieved — Tubing Only

*Air Cool Forgings 1775/1 Hr. Air Cool + 1100/8Hrs. Air Cool Plate 1650/1 Hr. Air Cool + 1100/8Hrs. Air Cool

Appendix 1: Properties of Titanium Grades (continued)

		Alpha-Beta Alloy	Alpha-Beta Alloy	Alpha-Beta Alloy	Beta Alloy
Designation		**Ti-6Al-2Sn-4Zr-6Mo**	**Ti-8Al-1Mo-1V**	**Ti-6Al-6V-2Sn**	**Ti-3Al-8V-6Cr-4Zr-4Mo**
Chemical Composition (percent)	(Max. values unless range is shown)	.10 C;.15 Fe;.04 N;.15 O;5.5/6.5 Al;1.8/2.2 Sn;3.6/4.4 Zr;5.5/6.5 Mo;.0125 H (bar)	.08 C;.30 Fe;.05 N;.12 O;7.35/8.35 Al;.75/1.25 Mo;.75/1.25 V; H_2 .0125(bar) .0150(forging)	.05 C;.04 N;.20 O;5.0/6.0 Al;5.0/6.0 V;1.5/2.5 Sn;.35/1.0 Fe;.35/1.0 Cu;.0150H_2(bar,sheet,plate)	.05 C;.03 N;.14 O;3.0/4.0 Al;7.5/8.5 V;5.5/6.5 Cr;3.5/4.5 Zr;3.5/4.5 Mo
Mill Annealed Tensile Properties		**Guar.R.T. Min. Prop. (S.T.A.)** 1100°F 8 Hrs. Air Cool			**Guar.R.T. Min. (S.T.A.)** 850-1000°F 8Hrs.Min. Air Cool
Ultimate Strength (psi)		170,000	130,000	150,000	180,000
Yield Strength (psi) 0.2% offset		160,000	120,000	140,000	170,000
Elongation in 2" (%) Sheet>0.025 thick		10		10	6
Reduction in Area (%) Bar		20		20	
Charpy V-Notch Impact (ft.-lbs.) @ Rm. Temp.			15-25	10-14	
Bend Radius	Under 0.070" thick		4.0 × Thickness	4.0 × Thickness	3.0 (S/t only)
	0.070" and Over		4.5 × Thickness	4.5 × Thickness	3.5 (S/t only)
Welded Bend Radius			6-10 × Thickness		
Hardness			R_C36	R_C38	
Physical Properties					
Beta Transus (F ± 25)		1720	1900	1735	1460
Coefficient of Thermal Expansion (10^{-6}in./in./F)	32-212	4.8	4.7	5.0	4.9
	32-600	5.7	5.0	5.2	5.2
	32-1000	5.8	5.6	5.3	5.4
	32-1200		5.7		
	32-1500				
Density (lbs./cu.in.)		0.169	0.158	0.164	0.174
Melting Point, Approx. (F)				3100	3000
Electrical Resistivity (@ R.T. (Microhms cm)			199	157	
Modulus of Elasticity — Tension (10^6 psi)		16.0	18.5	16.5	15.0
Modulus of Elasticity — Torsion (10^6 psi)			6.7		6.0
Thermal Conductivity (Btu/hr./sq.ft./F/Ft.)		4.1 @ Rm. Temp.		4.2 @ Rm. Temp.	
Specific Heat (Btu/Lb./F) @ Rm. Temp.				.155	
Weldability		LIMITED	FAIR	LIMITED	FAIR
Annealing Temp. (F)	Full		*	1330-1550/2 Hrs. Air Cool or FC	1500/30 Min.-Air Cool
	Stress Relief		1100-1200 1 Hr. Air Cool	1100/2 Hrs. Air Cool	
Forging* Temp. (F)	Blocking	1600-1650	1850-1950	1650-1750	1600-1700
	Finishing	1550-1650	1750-1850	1550-1650	1600-1700
Available Mill Products		Bar; Billet	Bar; Billet; Extrusions; Plate; Sheet; Wire	Bar; Billet; Extrusions; Plate; Sheet; Wire	Bar; Billet; Castings; Extrusions; Pipe; Plate; Sheet; Wire
Typical Applications		Jet engine components requiring high tensile strength and intermediate creep strength.	Jet engine components requiring good creep strength, high strength at elevated temperatures.	Rocket engine case air frame applications including forgings, fasteners	Air frame high strength fasteners, rivets, torsion bars, springs, pipe for oil industry and geothermal applications.
Industry Specifications		AMS 4981	AMS 4915, 4916, 4972, 4973	AMS 4918, 4936, 4971, 4978, 4979	AMS 4957, 4958

Mechanical Properties (Typical)

		Ti-6Al-2Sn-4Zr-6Mo 800°F	Ti-6Al-2Sn-4Zr-6Mo 1,000°F	Ti-8Al-1Mo-1V 600°F	Ti-8Al-1Mo-1V 800°F	Ti-6Al-6V-2Sn 600°F	Ti-3Al-8V-6Cr-4Zr-4Mo
Stress to Rupture in Time Shown	Stress (psi)		110,000				
	Time (hrs.)		100Hrs.				
Stress and Time to Produce Elongation Shown (creep)	Stress (psi)	70,000		82,000	60,000	100,000	
	Time (hrs.)	100		100	100	150	
	Creep (%)	0.2		0.2	0.2	0.2	

*Maximum Material Temperature in Furnace

*Duplex sheet 1450/1-8Hrs. FC + 1450/15Min. Air Cool Forgings 1850/1Hr. Air or faster + 1100/8Hrs. Air Cool

Beta Alloy	Beta Alloy	Beta Alloy
Ti-10V-2Fe-3Al	**Ti-13V-11Cr-3Al**	**Ti-15V-3Cr-3Sn-3Al**
.05 C;.05 N;.13 O;1.6/2.2 Fe; 2.6/3.4 Al;9.0/11.0 V;0.015 H_2	.05 C;.05 N;.17 O_2;.35 Fe; 12.5/14.5 V;10/12 Cr;2.5/3.5 Al; H_2 .0250 (bar, billet)	.05 C;.03 N;.13 O;.30 Fe; 14/16 V;2.5/3.5 Cr; 2.5/3.5 Sn; 2.5/3.5 Al;0.150 H_2
Guar.R.T. Min. (S.T.A.)	**Guar.R.T. Min. Prop. (S.T.A.)**	**Guar.R.T. Min. Prop. (S.T.A.)**
900-950°F Age	900°F (2-60 Hr.)	1,000°F 8 Hrs. Air Cool
170,000	170,000	145,000
160,000	160,000	140-170,000
6	4	7
600°F		
140,000		
100		
100,000		
100		
0.2%		
	3.0 (S/n only)	4 (S/t only)
	3.5 (S/n only)	5 (S/t only)
1460	1325	1400
4.9		
5.2	5.4(400°F)	5.4(800°F)
5.4	5.9	
0.174	0.175	0.172
3000		
	140/150	
15.0	15.0	13.5/16.5
6.0	6.2	
	4.0 @ Rm. Temp.	
FAIR	GOOD	GOOD
To ½ in. thick 1500/30 min.	1450-15 Min. Air Cool	1450 (Sol Anneal)
	900/4 Hrs. (STA Cond.)	
1600-1700	1950-2150	1800-2000
1600-1700		1500-1700
Sheet; Plate; Bar; Billet; Wire	Sheet; Strip; Plate; Forgings; Wire	Casting; Seamless tubing; Sheet; Strip
High strength air frame components	High strength air frame components including wire springs.	High strength aircraft and aerospace components.
AMS 4983; 4984; 4986; 4987	AMS 4917; 4959	AMS 4914

Appendix 2: Titanium Corrosion Rate Data

Commercially Pure Grades

C = Concentration %
T = Temperature °F (°C)
R = Corrosion rate, mpy (mm/y)

Media	C	T	R
Acetaldehyde	75	300(149)	0.02(0.001)
	100	300(149)	nil
Acetic acid	5 to 99.7	255(124)	nil
Acetic anhydride	99.5	boiling	0.5(0.013)
Acidic gases containing CO_2, H_2O, Cl_2, SO_2, SO_3 H_2O, O_2, NH_3	—	100-500 (38-260)	<1.0(<0.025)
Adipic acid	67	450(232)	nil
Aluminum chloride, aerated	10	212(100)	0.09(0.002)*
Aluminum chloride, aerated	25	212(100)	124(3.15)*
Aluminum fluoride	saturated	room	nil
Aluminum nitrate	saturated	room	nil
Aluminum sulfate	saturated	room	nil
Ammonium acid phosphate	10	room	nil
Ammonia anhydrous	100	104(40)	<5.0(<0,127)
Ammonium acetate	10	room	nil
Ammonium bicarbonate	50	212(100)	nil
Ammonium bisulfite pH2.05	spent pulping liquor	159(71)	0.6(0.015)
Ammonium chloride	saturated	212(100)	<0.5(<0.013)
Ammonium hydroxide	28	room	0.1(0.003)
Ammonium nitrate	28	boiling	nil
Ammonium nitrate + 1% nitric acid	28	boiling	nil
Ammonium sulfate	10	212(100)	nil
Aqua regia	3:1	room	nil
Aqua regia	3:1	175(79)	34.8(0.884)
Barium chloride	25	212(100)	nil
Barium hydroxide	saturated	room	nil
Barium nitrate	10	room	nil
Barium fluoride	saturated	room	nil
Benzoic acid	saturated	room	nil
Boric acid	saturated	room	nil
Boric acid	10	boiling	nil
Bromine	liquid	86(30)	rapid
Bromine moist	vapor	86(30)	<0.1(<0.003)
N-butyric acid	undiluted	room	nil
Calcium bisulfite	cooking liquor	79(26)	0.02(0.001)
Calcium carbonate	saturated	boiling	nil
Calcium chloride	5	212(100)	0.02(0.005)*
Calcium chloride	10	212(100)	0.29(0.007)*
Calcium chloride	55	220(104)	0.02(0.001)*
Calcium hydroxide	saturated	boiling	nil
Calcium hypochlorite	6	212(100)	0.05(0.001)
Calcium hypochlorite	18	70(21)	nil
Calcium hypochlorite	saturated slurry	—	nil
Carbon dioxide	100	—	excellent
Carbon tetrachloride	vapor & liquid	boiling	nil
Chlorine gas, wet	>0.7H_2O	room	nil
Chlorine gas, wet	>1.5H_2O	392(200)	nil
Chlorine header sludge and wet chlorine	—	207(97)	0.03(0.001)
Chlorine gas, dry	<0.5H_2O	room	may react
Chlorine dioxide in steam	5	210(99)	nil
Chlorine trifluoride	100	<86(30)	vigorous reaction
Chloracetic acid	100	boiling	<5.0(<0.127)
Chlorosulfonic acid	100	room	7.5-12.3 (0.191-0.312)
Chloroform	vapor & liquid	boiling	0.01(0.000)
Chromic acid	10	boiling	0.1(0.003)
Chromic acid	50	180(82)	1.1(0.028)
Chromic acid + 5% nitric acid	5	70(21)	<0.1(<0.003)
Citric acid	50	140(60)	0.01(0.000)
Citric acid	50 aerated	212(100)	<5.0(<0.127)
Citric acid	50	boiling	5.50 (0.127-1.27)
Cupric chloride	40	boiling	0.2(0.005)
Cupric chloride	55	246(119) (boiling)	0.1(0.003)
Cupric cyanide	saturated	room	nil
Cuprous chloride	50	194(90)	<0.1(<0.003)
Cyclohexane	—	302(150)	0.1(0.003)

* May corrode in crevices. ** Grades 7 and 12 immune.

Media	C	T	R
Dichloroacetic acid	100	boiling	0.29(0.007)
Dichlorobenzene + 4-5% HCl	—	355(179)	4(0.102)
Diethylene triamine	100	room	nil
Ethyl alcohol	95	boiling	0.5(0.013)
Ethylene dichloride	100	boiling	0.2-5.0 (0.005-0.127)
Ethylene diamine	100	room	nil
Ferric chloride	10-20	room	nil
Ferric chloride	10-50	boiling	nil
Ferric chloride	50	302(150)	0.1(0.003)
Ferric sulfate	10	room	nil
Fluoboric acid	5-20	elevated	rapid
Fluorosilicic	10	room	1870(47.5)
Food products	—	ambient	no attack
Formaldehyde	37	boiling	nil
Formic acid aerated	25	212(100)	0.04(0.001)**
Formic acid aerated	90	212(100)	0.05(0.001)**
Formic acid	25	212(100)	96(2.44)**
non-aerated	90	212(100)	118(3.00)**
Furfural	100	room	nil
Gluconic acid	50	room	nil
Glycerin	—	room	nil
Hydrogen chloride	dry gas	ambient	nil
Hydrochloric acid	1	boiling	>100(>2.54)
Hydrochloric acid	5	boiling	400(10.2)
chlorine saturated	5	374(190)	<1(<0.025)
	10	374(190)	>1120(>28.5)
+5% HNO_3	5	200(93)	1.2(0.030)
+5% HNO_3	1	boiling	2.9(0.074)
+0.5% CrO_3	5	200(93)	1.2(0.031)
+1% CrO_3	5	100(38)	0.72(0.018)
+0.05% $CuSO_4$	5	200(93)	3.6(0.091)
+0.5% $CuSO_4$	5	200(93)	2.4(0.061)
+0.5% $CuSO_4$	5	boiling	3.3(0.084)
Hydrofluoric acid	1.48	room	rapid
Hydrogen peroxide	6	room	<5(<0.127)
Hydrogen peroxide	30	room	<12(<0.305)
Hydrogen sulfide	7.65, moist	200-230 (93-110)	nil
Hypochlorous acid + ClO_2 and Cl_2	17	100(38)	0.001(0.000)
Iodine in water + Potassium Iodide	—	room	nil
Lactic acid	10-85	212(100)	<5.0(<0.127)
Lead acetate	saturated	room	nil
Linseed oil, boiled	—	room	nil
Lithium chloride	50	300(149)	nil*
Magnesium chloride	5-40	boiling	nil*
Magnesium hydroxide	saturated	room	nil
Magnesium sulfate	saturated	room	nil
Maganous chloride	5-20	212(100)	nil
Maleic acid	18-20	95(35)	0.6(0.002)
Mercuric chloride	saturated	212(100)	<5(<0.127)
Mercuric cyanide	saturated	room	nil
Methyl alcohol	91	95(35)	nil
Nickel chloride	20	212(100)	0.11(0.003)
Nitric acid, aerated	50	room	0.08(0.002)
Nitric acid, aerated	70	room	0.18(0.005)
Nitric acid, aerated	10	104(40)	0.10(0.003)
Nitric acid, aerated	70	158(70)	1.56(0.040)
Nitric acid, aerated	40	392(200)	24(0.610)
Nitric acid, aerated	20	554(290)	12(0.305)
Nitric acid, non-aerated	70	176(80)	1-3 (0.025-0.076)
Nitric acid	17	boiling	3-4 (0.076-0.102)
Nitric acid	35	boiling	5-20 (0.127-0.508)
Nitric acid	70	boiling	2.5-37 (0.064-0.940)
Nitric acid	—	room	0.1(0.003)
white fuming		360(160)	<5.0(<0.127)
Nitric acid red fuming	<about 2%H_2O	room	ignition sensitive
Nitric acid red fuming	>about 2%H_2O	room	not ignition sensitive
Nitric acid + 10% $FeCl_3$	40	boiling	4.8-7.4 (0.122-0.188)

Appendix 2: Titanium Corrosion Rate Data
Commercially Pure Grades

C = Concentration %
T = Temperature °F (°C)
R = Corrosion rate, mpy (mm/y)

Media	C	T	R
Nitric acid + 10% NaClO	40	boiling	0.12-1.40 (0.003-0.036)
Oil well crudes	—	ambient	0.26-23.2 (0.007-0.589)
Oxalic acid	1	boiling	4247(107.9)
Oxalic acid	25	140(60)	470(11.9)
Phenol	saturated solution	70(21)	4.0(0.102)
Phosphoric acid	10-30	room	0.8-2 (0.020-0.051)
Phosphoric acid	30-80	room	2-30 (0.051-0.762)
Phosphoric acid	1	boiling	10(0.254)
Phosphoric acid + 3% nitric acid	81	190(88)	15(0.381)
Phosphorous oxychloride	100	room	0.14(0.004)
Phosphorous trichloride	saturated	room	nil
Pthalic acid	saturated	room	nil
Potassium bromide	saturated	room	nil
Potassium chloride	saturated	room	nil
Potassium ferricyanide	saturated	room	nil
Potassium hydroxide	50	80(29)	0.4(0.010)
Potassium hydroxide	10	boiling	<5.0(<0.127)
Potassium hydroxide	25	boiling	12(0.305)
Potassium sulfate	10	room	nil
Potassium thiosulfate	1	—	nil
Salicylic acid (Na salt)	saturated	room	nil
Seawater	—	76(24)	nil
Sebacic acid	—	464(240)	0.3(0.008)
Silver nitrate	50	room	nil
Sodium acetate	saturated	room	nil
Sodium aluminate	25	boiling	3.6(0.091)
Sodium bifluoride	saturated	room	rapid
Sodium bisulfate	saturated	room	nil
Sodium bisulfate	10	150(66)	72(1.83)
Sodium chloride pH1.5	23	boiling	nil*
Sodium chloride pH1.2	23	boiling	28(0.711)*
Sodium chloride pH1.2 some dissolved chlorine	23	boiling	nil*
Sodium citrate	saturated	room	nil
Sodium cyanide	saturated	room	nil
Sodium dichromate	saturated	room	nil
Sodium fluoride	saturated	room	0.3(0.008)
Sodium bisulfite	25	boiling	nil
Sodium carbonate	25	boiling	nil
Sodium chlorate	saturated	room	nil
Sodium hydroxide	5-30	70(21)	>0.12 (>0.001)
Sodium hydroxide	10	boiling	0.84(0.021)
Sodium hydroxide	40	176(80)	5.0(0.127)
Sodium hydroxide	50	135(57)	0.5(0.0127)
Sodium hydroxide	73	265(129)	7.0(0.178)
Sodium hydroxide	50-73	370(188)	>43(>1.09)
Sodium hypochlorite	6	room	nil
Sodium nitrate	saturated	room	nil
Sodium phosphate	saturated	room	nil
Sodium silicate	25	boiling	nil
Sodium sulfate	10-20	boiling	nil
Sodium sulfide	saturated	room	nil
Sodium sulfite	saturated	boiling	nil
Sodium thiosulfate	25	boiling	nil
Soils, corrosive	—	ambient	nil
Stannic chloride	24	boiling	1.76(0.045)
Stannic chloride	saturated	room	nil
Steam + air	—	180(82)	0.01(0.000)
Succinic acid	100	365(185)	nil
Sulfamic acid	3.75g/l	boiling	nil
Sulfamic acid	7.5g/l	boiling	108(2.74)
Sulfamic acid + .375g/l $FeCl_3$	7.5g/l	boiling	1.2(0.030)
Sulfur dioxide, water saturated	near 100	room	0.1(0.003)
Sulfur dioxide gas + small amount SO_3 and approx 3% O_2	18	600(316)	0.2(0.006)

Media	C	T	R
Sulfuric acid, aerated	3	140(60)	0.5(0.013)
	5	140(60)	190(4.83)
	3	212(100)	920(23.4)
	concentrated	room	62(1.57)
Sulfuric acid	1	boiling	700(17.8)
Sulfuric acid + 0.25% $CuSO_4$	5	200(93)	nil
+ 0.25% $CuSO_4$	30	100(38)	2.4(0.061)
+ 0.5% CrO_3	30	200(93)	nil
+ 1.0% $CuSO_4$	30	boiling	65(1.65)
Sulfuric acid vapors	96	150(66)	nil
Sulfuric acid, + 10% HNO_3	90	room	18(0.457)
+ 70% HNO_3	30	room	4.0(0.102)
+ 90% HNO_3	10	room	nil
Sulfuric acid saturated with chlorine	62	60(16)	0.07(0.002)
Sulfuric acid saturated with chlorine	5	374(190)	<1(<0.025)
Sulfuric acid + 4.79 g/l Ti^{+4}	40	212(100)	passive
Sulfurous acid	6	room	nil
Tannic acid	25	212(100)	nil
Tartaric acid	10-50	212(100)	<5(<0.127)
Terepthalic acid	77	425(218)	nil
Tetrachloroethane, liquid and vapor	100	boiling	0.02(0.001)
Tetrachloroethylene + H_2O	—	boiling	5(0.127)
Tetrachloroethylene	100	boiliing	nil
Titanium tetrachloride	99.8	572(300)	62(1.57)
Titanium tetrachloride	concentrated	room	nil
Trichloroacetic acid	100	boiling	573(14.6)
Trichloroethylene	99	boiling	0.1-5 (0.003-0.127)
Urea + 32% ammonia, + 20.5% H_2O, 19% CO_2	28	360(182)	3.1(0.079)
Water, degassed	—	600(316)	nil
X-ray developer solution	—	room	nil
Zinc chloride	20	220(104)	nil*
Zinc chloride	50	302(150)	nil*
Zinc chloride	75	392(200)	24(0.610)*

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