

*Materials Compatibility and Corrosion Issues
for Accelerator Transmutation of Waste*

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MATERIALS COMPATIBILITY AND CORROSION ISSUES FOR ACCELERATOR TRANSMUTATION OF WASTE

by

Karl Staudhammer

ABSTRACT

The need to understand the materials issues in an accelerator transmutation of waste (ATW) system is essential. This report focuses on the spallation container material, as this material is exposed to some of the most crucial environmental conditions of simultaneous radiation and corrosion in the system. The most severe design being considered is that of liquid lead. In previous investigations of lead compatibility with materials, the chemistry of the system was derived solely from the corrosion products; however, in an ATW system, the chemistry of the lead changes not only with the derived corrosion products of the material being tested but also with the buildup of the daughter production with time. Daughter production builds up and introduces elements that may have a great effect on the corrosion activity of the liquid lead. Consequently, data on liquid lead compatibility can be regarded only as a guide and must be reevaluated when particular daughter products are added. This report is intended to be a response to specific materials issues and concerns expressed by the ATW design working group and addresses the compatibility/corrosion concerns.

OVERVIEW

Materials compatibility and corrosion issues in an Accelerator Transmutation of Waste (ATW) system appear to be at first glance a straightforward problem. The question is easy: find a material that will work (if possible, up to 30 years) and contain the various environments. However, we soon realize that the problem is far more complex. Compatibility issues exist in the spallation target, the D_2O carrier/coolant, and a fused salt loop. Currently, we are focusing on the spallation container material; the other two systems will be discussed at a later time. At this point the choices for a spallation source include liquid lead, solid lead pebbles, and a solid tungsten core. Each of these designs is physically different and has specific compatibility issues; the most severe design is that of the liquid lead. For the two solid target designs, the compatibility issues are far less severe and will be dealt with separately.

Materials compatibility with liquid lead was extensively investigated from the late 1940s to the late 1960s. All the collected data were based on a fixed initial purity of the lead where the impurities in the lead, with time, were derived solely from the corrosion products between lead and the solid material being tested. However, this is not the case for ATW, where the chemistry of the lead not only changes with the derived corrosion products of the material being tested but also changes because of the buildup of the daughter production with time. Daughter production, while small at first, will build up and introduce elements that may have a great effect on the corrosion activity of the liquid lead. Specific elements, e.g., zirconium, in liquid bismuth can greatly reduce the initial corrosion of iron alloys while mercury in liquid bismuth enhances corrosion. Consequently, data on liquid lead compatibility can be regarded only as a guide and must be reevaluated with the addition of particular daughter products. In addition, the majority of published liquid lead compatibility data falls in a temperature range of 600° to 800°C , which is higher than the anticipated ATW liquid lead operating temperature range of 400° to 500°C .

This report is intended to be a response to specific materials issues and concerns expressed by the ATW design working group and addresses the compatibility/corrosion concerns. To facilitate the basic understanding, background, and terminology for the ATW community, the appendices provide a short synopsis of corrosion issues in general, along with pertinent published data for currently discussed ATW materials.

SPECIFIC MATERIALS CONSIDERED FOR AN ACCELERATOR TRANSMUTATION OF WASTE (ATW) SYSTEM

The major corrosion considerations in an ATW environment involve finding materials that will not only withstand liquid lead but also be radiation resistant. Three relatively simple solutions can address these corrosion issues: (1) use a corrosion-resistant material, (2) change the environment, and (3) protect the material. Although these solutions may oversimplify the process of corrosion control, they do indicate steps to be used in stopping corrosion. In an ATW system, items (1) and (3) have the greatest potential for controlling corrosion; although (2) is essentially fixed by the requirements of the system, some possibilities do exist.

One way by which we can change materials to minimize or stop corrosion is to use a more corrosion-resistant material, usually an alloy (HT-9 was so conceived for radiation resistance), or occasionally by upgrading the material to a more resistant material. In addition to changing materials by alloying, we can also choose nonmetallic materials such as polymers and ceramics, including graphite. The use of polymers in an ATW system, particularly in and around the spallation source, appears to be out of the question due to the unfavorable properties at elevated temperatures and high radiation environments. Although ceramics are excellent for high temperature, they do not, for the most part, survive the radioactive environment well (although there are some exceptions). These exceptions, however, do not have the data base at the high fluence levels anticipated for the ATW system. The matter of changing materials is not merely a function of selecting material that has approved corrosion resistance; we must also consider other factors, such as thermal properties, ease of fabrication, low thermal neutron cross sections, radiation hardenability, and all the other aspects previously indicated.

Every material has at least one "Achilles' heel," if not more. We must always consider these weaknesses when selecting a material for a given part. In fact, from a design point, we must be aware of the drawbacks associated with a specific material and ensure that these factors are not detrimental to a given use.

When we speak of changing the environment to reduce corrosion, the easiest and most obvious method is to lower the temperature. Because corrosion processes are chemical reactions, every 10°C decrease in temperature reduces the reaction rate by half.¹ Thus, the lower the temperature, the more the rate of corrosivity is retarded (not eliminated). In addition, the atmosphere can be changed by the presence of certain gases; some metals are corroded in the absence of oxygen and others in the presence of oxygen. Other environmental changes involve agitation and velocity, both of which have a decided

influence on many materials. For aqueous systems, a fairly easy change in some processes is that of adjustment of the pH, which is the measure of the acidity or basicity of the solution. For most materials, an increase in the pH to the alkaline side reduces the corrosivity. The presence of trace additives can influence the environment in either good or bad ways. Certain inhibitors can also be added that suppress the corrosivity of the main species in aqueous solutions. This method is better understood and more widely applied in aqueous systems than in the liquid metals.

Appendix A is included to help delineate the major corrosion categories and issues applicable in an ATW environment.

SPALLATION SOURCE (LIQUID LEAD COMPATIBILITY)

Aluminum and Aluminum Alloys

Aluminum is a versatile material that has a broad range of uses. Its low density and high specific strength (strength-to-weight ratio) are very attractive. Its density is 2.70 gm/cm³, approximately one-third of that of steel, copper, or brass. Aluminum has a high resistance to corrosion in atmospheric environments, in fresh and sea water, and in many chemicals and their solutions. The preeminent reason for alloying aluminum is to increase its mechanical properties (strength, hardness, and resistance to fatigue, creep, or wear). In many alloys, other characteristics are either primary or important supplementary reasons for the amounts and types of alloying elements used.

The maximum alloy content (total of all alloying elements) included in the wrought alloys is about 11%, primarily so that the workability of the face centered cubic (fcc) structure is retained. For ATW, a wrought material is preferred for ease of construction. Many effects of alloying elements on microstructure can be predicted from and related to the equilibrium phase diagrams. Pure unalloyed aluminum is a single-phase material and is composed only of grains and grain boundaries, which would be the same for the solid solutions formed with pure aluminum by any of the alloying elements. Some phase diagrams that illustrate a solid solution field at the aluminum end of the diagram are shown in Fig. 1.² Alloying element contents that exceed the solubility limit produce “second phase” microstructural constituents that may consist of either the pure alloying ingredient or an intermetallic compound.

Although major differences in properties and characteristics usually require alloying additions of one to several percent, many alloying elements produce highly significant effects when added in small fractions of a percent or when increased by such small

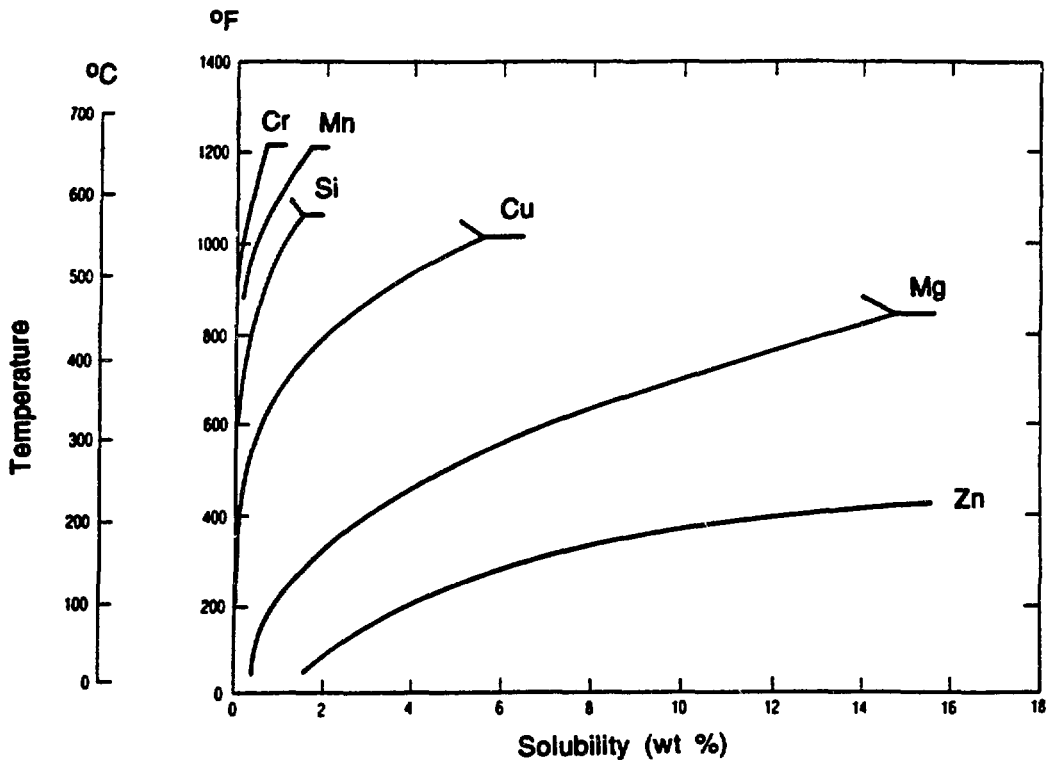


Fig. 1. Equilibrium binary solid solubility as a function of temperature for alloying elements most frequently added to aluminum.

amounts. The interactions are quite complex and, for a given element, may be either highly beneficial or highly detrimental, depending on the other elements involved. The presence or absence of amounts on the order of one thousandth of one percent of certain impurities, e.g., sodium or calcium, can have a great effect.

Aluminum and Aluminum Alloys in Liquid Lead

The aluminum-lead equilibrium phase system is shown in Fig. 2.^{3,4,5} Aluminum and lead form no compounds and are immiscible in one another. The solid solubility of aluminum in lead is practically nil,⁴ whereas the solubility of aluminum in liquid lead is measurable and is shown in Fig. 3.^{1,6} The operating temperature range for a liquid lead ATW system is in the 400° to 600°C range; thus, a maximum solubility of 0.1 wt. % would be experienced. This, figure however, is far too high. The aluminum container would be slowly consumed by the lead, which would preclude the use of an aluminum alloy as a container material for liquid lead. The primary usage of aluminum alloys as

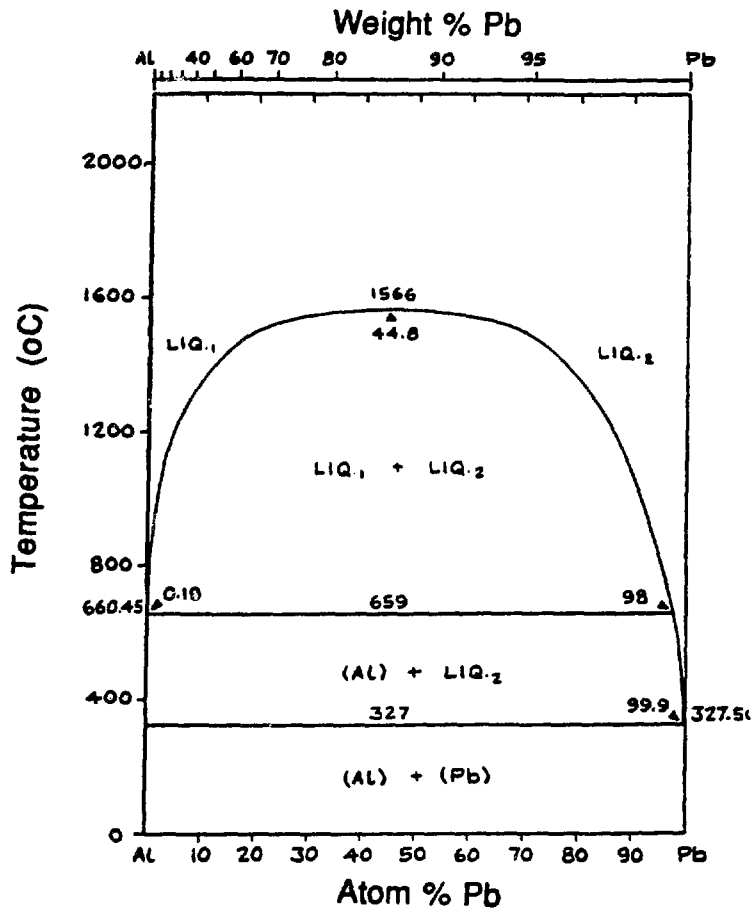


Fig. 2. Aluminum-lead equilibrium phase diagram.

container materials was envisioned for solid targets. This, however, does not necessarily eliminate aluminum alloys in liquid lead systems if the aluminum alloy can be clad or otherwise protected from contact with the liquid lead. However, as a free-standing container material, it is not recommended.

Aluminum alloy 6061 has good strength, formability, weldability, and very good resistance to a number of environments. Its nominal composition and specific properties are listed in Appendix B.

Aluminum alloy 5000-3Mg has been irradiated in at the Los Alamos Meson Physics Facility (LAMPF) and has a nominal irradiation data base. It is not a standard aluminum alloy (Al-3 wt. % Mg), although 5252 is very close, its composition being Al-2.5 wt. % Mg. This alloy, for the reasons previously stated, would be equally undesirable in a liquid lead system.

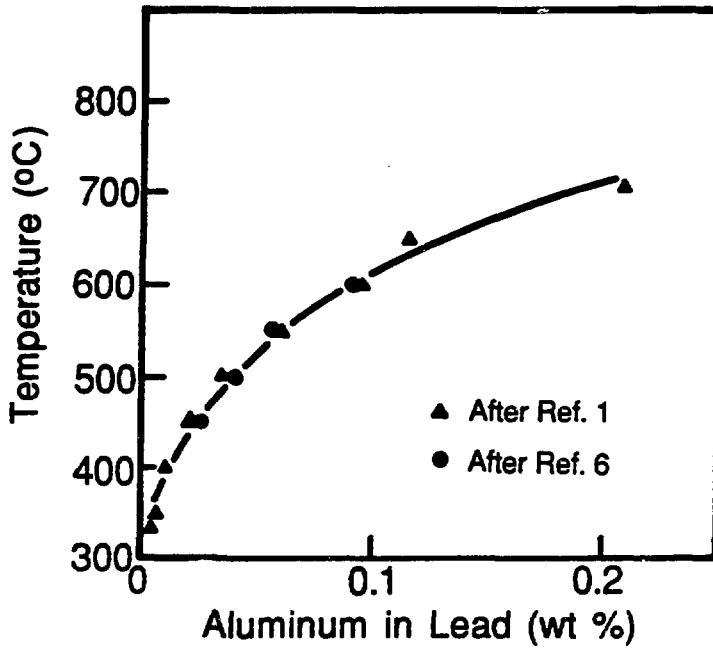


Fig. 3. Solubility of aluminum in liquid lead.

Inconel 718

Inconel 718, a nickel-based, high temperature alloy, has been used as a beam window material in past runs at LAMPF in which solid targets were used. Currently this is the only envisioned usage. In addition, tests in liquid lead on nickel alloys revealed these alloys to be unsuitable.⁴ The data sheet on Inconel 718 is included in Appendix C.

Zirconium and Its Alloys

For nuclear applications zirconium and its alloys are among the most unusual materials available today. In the production of zirconium metal, hafnium is found as an impurity because it occurs naturally with zirconium in the ores. Typical hafnium impurity levels are around 4% maximum for nonnuclear grade alloys. For most applications, the hafnium does not significantly influence the physical or mechanical properties of zirconium, but it does affect its nuclear properties. Hafnium has a high thermal neutron capture cross section (113 barns) as compared with zirconium which has a low thermal neutron capture cross section (0.18). Some of the properties of zirconium and hafnium are given in Table I.

Table I. Properties of Zirconium and Hafnium.

Property	Zirconium	Hafnium
Atomic number	40	72
Atomic weight	91.22	178.5
Density	6.5 g/cm ³ 0.234 lb/in. ³	13.09 g/cm ³ 0.47 lb/in. ³
Melting point	1845°C	2222°C
Boiling point	3577°C	3100°C
Allotropic transformation	865°C	1760°C
Lattice parameters		
alpha hexagonal close packed	a = 3.2312 Å (25°C) c = 5.1477 Å (25°C)	3.1883 Å 5.0422 Å
beta body centered cubic	a = 3.6090 Å (862°C)	3.50Å
Thermal expansion	5.8 x 10 ⁻⁶ /°C	5.9 x 10 ⁻⁶ /°C
Thermal conductivity	100°C, 0.049 cal/s/cm/°C	50°C, 0.223 W/cm/°C
Specific heat	0.067 cal/g/°C	0.035 cal/g/°C
Electrical resistivity	40 μΩ/cm	35.1 μΩ/cm
temperature coefficient	4.4 x 10 ⁻³ /°C	4.4 x 10 ⁻³ /°C
Heat of fusion	60.3 cal/g	...
Heat of vaporization	1560 cal/g	...

Zirconium and its alloys are defined by the following terms:

Commercial grade zirconium designates unalloyed zirconium containing the natural occurring hafnium.

Reactor grade zirconium designates unalloyed zirconium from which most of the hafnium has been removed to make it suitable for nuclear applications. Currently this implies less than 100 ppm hafnium.

Zircaloy is used to designate a series of zirconium, tin, iron, chromium, and nickel alloys. *Zircaloy-2* and *Zircaloy-4* are the most commonly used alloys in the nuclear industry. They are often designated as reactor grade *Zircaloy-2* or *-4*. The composition and physical properties of *Zircaloy-2* and *-4* are given in Tables II and III. The two alloys differ only slightly in chemical composition and, in fact, *Zircaloy-4* was developed when it was discovered that nickel in the *Zircaloy-2* promoted the absorption of hydrogen, which was undesirable. *Zircaloy-4* has additional iron replacing the nickel. It should be noted that the crystal structure of zirconium is hexagonal close packed (hcp) rather than cubic,

Table II. Alloy Composition of Zircaloy-2 and -4.

Tin	1.2 to 1.7	1.2 to 1.7
Iron	0.07 to 0.20	0.18 to 0.24
Chromium	0.05 to 0.15	0.07 to 0.13
Nickel	0.03 to 0.08	...
Oxygen	0.12 typical	0.12 typical

Table III. Physical Properties of Zircaloy-2 and -4.

Density	0.237 lb/in. ³
Hardness annealed	170 to 187 HB
87 to 95 Rockwell hardness B scale	
Electrical resistivity	74 $\mu\Omega/cm$
Elastic modulus	
tension, psi	14 000 000
torsion or shear, psi	5 200 000
Impact	
Charpy V-notch at room temperature	7 to 15 ft lb
Coefficient of thermal expansion	
in./in./°F 80 to 212°F	3.24×10^{-6}
80 to 1000°F	3.6×10^{-6}
Crystal structure	hexagonal close packed a = 3.2312A, c = 5.1477A

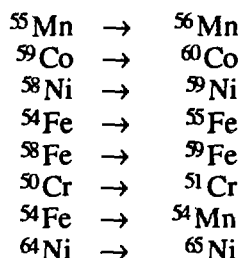
which makes many of its properties anisotropic. A compilation of assorted data on Zircaloy-2 and -4 is provided in Appendix D.

Limited data on liquid lead compatibility exists for zirconium. The corrosion rate is affected by trace impurities such as oxygen, hydrogen, or nitrogen in the molten metal. Zirconium has a corrosion rate of less than 1 mil/year in liquid lead to 600°C. Molten metals that are known to severely attack zirconium are zinc, bismuth, and magnesium. This may pose a problem in the usage of a liquid lead spallation target, as all elements will be present in increasing amounts due to daughter production. However, only bismuth (at least initially) will pose any significant concern.

Steels

The special requirements of nuclear physics have been reflected in the technology of stainless steels in four major areas: (1) steel quality, (2) neutron loss, (3) induced radioactivity, and (4) compatibility with the heat transfer media. The last three have forced

certain changes in compositions of the steels, whereas the first has led to a general improvement in quality. In an ATW system, neutron economy must be maintained by minimizing (or eliminating) the amount of high cross-section alloy additions. The average cross section of stainless steel is approximately two to three barns. When steels are selected for ATW, particular attention must also be paid to item (3) to minimize the problem of induced radioactivity. Predominantly, the alloying elements of concern in steel are:



From the viewpoint of physical properties, some of the most interesting features of nuclear applications are the radiation effects of transformation reactions: This leads to a whole new branch of metallurgy-radiation alteration via transmutation.

442 stainless steel is a nonstandard grade of wrought ferritic body centered cubic (bcc) steel. Its composition is 21 chromium, 0.5 silicon, 0.5 manganese, 0.06 carbon and balance iron all in weight percent. It is a steel that must be annealed above 473°C but below the austenitic transformation temperature to eliminate transformation products during welding. Type 442 steel most closely resembles type 446 steel⁷ (see Fig. 4). Its corrosion rate in liquid lead is, however, expected to be high.

Croloy is an alloy found to be very compatible in a liquid lead/bismuth eutectic up to 450°C.⁸ Data on liquid lead and Croloy are not available; however, it is known that for many elements, liquid lead has a ten fold reduction in solubility going from bismuth to lead with lead/bismuth eutectic lying about midway between.⁹ Both chromium and nickel are more soluble than iron, and with high chromium and nickel alloys, i. e., stainless steels, selective leaching of these components takes place, leaving an iron-rich surface.⁶ Chromium is not leached as fast as nickel and there appears to be an interaction effect causing chromium to be reprecipitated as the nickel dissolves. It has been reported that if the chromium content of the alloys is increased above 2.5%, severe corrosion will take place.⁶ The tested alloys that showed no corrosion were:

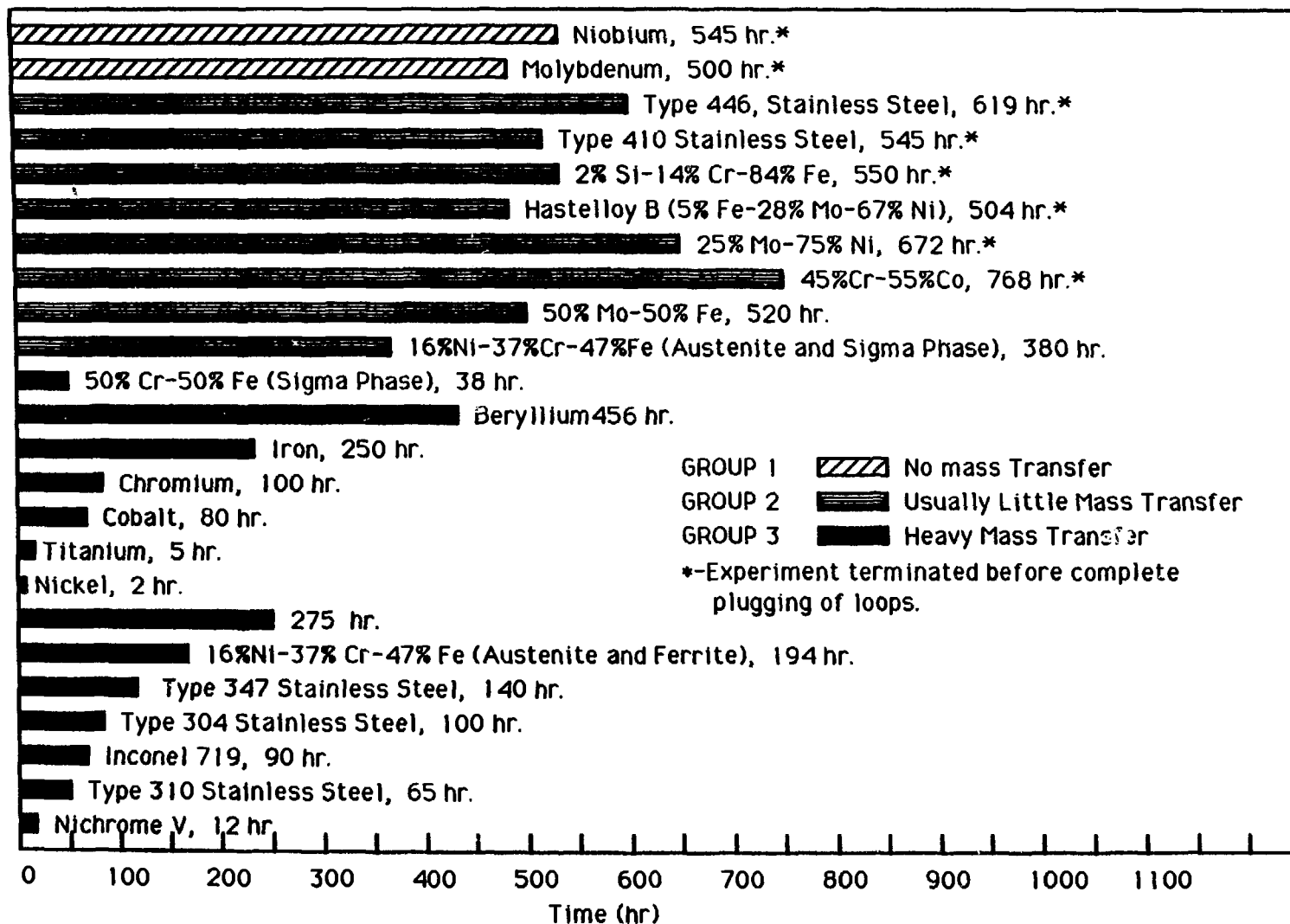


Fig. 4. Mass transfer in liquid lead.

Croloy 0.5	0.5 Cr, 0.5 Mo bal. Fe	500°–400°C	>24,000 hr
Croloy 1.25	1.25 Cr, 0.5 Mo bal. Fe	500°–400°C	10,000 hr
Croloy 1.25		525°–425°C	20,000 hr
Croloy 2.25	2.25 Cr, 1.0 Mo bal. Fe	500°–400°C	10,000 hr

These data indicate that low chromium content in an ATW system will be a requirement. It also appears that the maximum temperature at which uninhibited lead can be contained in Croloy 1.25 is 400°C. Croloy 0.5 would be a much better choice. Some tests have been performed on the inclusion of inhibitors, such as zirconium, titanium, and tellurium at the ppm level. The inhibiting action appears to be the formation of a carbide or nitride film on the surface of the steel between the inhibitor and the nitrogen or carbon present in the steel, which reduces the iron dissolution rate. For liquid lead/bismuth eutectic between 325° and 450°C, titanium is the more desirable inhibitor due to its greater solubility. However, ppm levels of magnesium were needed to protect the inhibitor from oxidation and subsequent depletion.

HT-9 is a ferritic (bcc) steel (developed at Hanford National Laboratory) that has exceptionally good radiation characteristics in high neutron flux. Its composition is 84.8 iron, 11.7 chromium, 1.0 molybdenum, 0.51 nickel, 0.71 manganese, 0.49 tungsten, and 0.31 vanadium all in weight percent. Again, the high chromium content would not suggest good corrosion resistance in liquid lead.

Liquid lead compatibility for specific alloys of interest appears to be a hit-or-miss proposition. However, the behavior of 24 materials that were tested in liquid lead has been reported.⁷ Figure 4 shows the results of this study, which were obtained in a closed quartz system operated at 800°C in the hot leg and 500°C in the cold leg, producing a ΔT of 300°C gradient. Flow rates of 1 ft/min were estimated. These temperatures are far in excess of those proposed for ATW. Nonetheless, these experiments provide a good guide. Still other work on the corrosion of steels in liquid lead (and bismuth) concluded that the corrosion of steels in uninhibited lead is about 40 times less than that in uninhibited bismuth under similar conditions.⁷ The corrosion is reduced by the addition of 500 ppm of titanium for low alloy steels with available nitrogen or carbon in the steels. Their test temperature was 800°C with a ΔT of 100°C. The smaller ΔT will, of course, decrease the mass transport as compared with data cited in Ref. 7. Table IV presents the data on relative corrosion rates.⁷

Table IV. Relative Corrosion Rates of Steels in Bismuth and Lead.

Steel	Bismuth	Bismuth (+500 ppm Zr) $\times 10^{-2}$	Lead $\times 10^{-2}$	Lead (+500 ppm Ti) $\times 10^{-3}$
0.3% carbon steel	1	1	3.2	1
Mild steel	1	1	3.4	1
CRM6	1.3	25	3.0	1
13% Cr-Fe	1.5	42	3.6	3.0
18-8 stainless steel	2.0	42	3.8	17.0

Note: Temperature 800°C, ΔT 100°C.

SPALLATION SOURCE (SOLID LEAD COMPATIBILITY)

The ATW target blanket working group has proposed that a spallation target consisting of a bed of lead pebbles would have (for equivalent designs) comparable production of neutrons per incident proton. The use of a lead pebble bed would for all practical purposes eliminate many of the liquid lead corrosion concerns.

Because this type of target must be cooled (helium at ≈ 5 atm or D_2O), the corrosion concerns of a liquid lead system will be replaced with aqueous corrosion concerns for the D_2O . The requirement for large volumes of high-pressure helium makes the D_2O option far more practical.

Unprotected lead cannot be used in water due to the formation of lead oxides, which do not form a tight protective film on the lead, though this is a strong function of pH and other dissolved impurities. In distilled water, lead is dissolved very slowly in proportion to the amount of dissolved oxygen.² In time lead oxide will spall off, allowing further corrosion to take place. The Paul Scherrer Institute (PSI), in Switzerland, has proposed the use of lead pebbles that are coated with tin,¹⁰ which has a far better corrosion resistance as well as a low thermal cross section.

With the lead pebble- D_2O system, low atomic number materials (low Z) such as the 5XXX and 6XXX series aluminum alloys have very good corrosion resistance and should be pH adjustable to prevent corrosion. Should this not be possible, a thin removable liner with very low corrosion rates in liquid lead, such as Zircaloy-2 or -4, can be included with the aluminum alloy, providing the mechanical strength.

HEAT EXCHANGER H₂O-MATERIALS COMPATIBILITY

Water is an attractive coolant and an obvious choice for the heat transfer material. In addition to its low cost, its nuclear properties are satisfactory with regard to absorption cross section and induced activity. However, the use of water primarily as a heat transfer medium in reactors has presented corrosion problems far more severe than those encountered in conventional steam generating plants. Depending on the type of reactor, the operating conditions can vary greatly. The water temperatures and pressures are overall considerably greater than those used in the past. These conditions impose very stringent requirements for structural materials that must withstand the corrosive action of water for extended periods without deterioration while maintaining structural integrity. As a consequence, considerable effort has been expended in the development of corrosion-resistant metals and alloys for cooling systems.

It is difficult to obtain comparative corrosion data; all conditions must be standardized and controlled as much as possible. This, of course, is not necessarily the case for published data from numerous sources spanning 40 years or more. Some of the more important factors that affect the data are (a) purity of the water, including dissolved gas content; (b) purity of metal (the corrosion resistance of metals and alloys may be appreciably affected by small amounts of impurities; the impurity content of the metal being considered should always be known); (c) surface preparation; and (d) specimen history, for example, cold work, hot work, stress relieved.

Some of the more promising materials having good corrosion resistance in water at high temperatures are discussed next.

Aluminum

The nominal chemical composition of representative aluminum wrought alloys is given in Appendix B. Included are typical tensile properties of these alloys in tempers (heat-treatment condition) representative of their most common use. Wrought alloys are of two types: non-heat-treatable, e.g., 1XXX, 3XXX, 4XXX, and 5XXX series, and heat-treatable, e.g., 2XXX, 6XXX, and 7XXX series. All non-heat-treatable alloys have a high resistance to general corrosion. Among the heat-treatable alloys, those of 6XXX series, which are moderate-strength alloys based on the quasi-binary Al-Mg₂Si system, provide a high resistance to general corrosion equal to or approaching that of non-heat-treatable alloys. The 5XXX series has an excellent resistance to corrosion by high-purity water.¹¹ A slight reduction takes place when alloys are first exposed to the water, but reduction

decreases to a low rate within a few days upon formation of a protective oxide film of equilibrium thickness on the alloys; pickup of aluminum by water then becomes negligible. Resistance of the alloys is not affected significantly by carbon dioxide and oxygen dissolved in the water.

The same types of alloys are also resistant to many natural waters.¹¹ In general, resistance is higher in neutral or slightly alkaline waters and less in acidic ones. Correlations of the compositions of various waters with their corrosivities in aluminum alloys have been developed, but none dependably predict the corrosivities of other waters.¹² Consequently, an ongoing testing and evaluation program is necessary for any aluminum alloy chosen for ATW applications.

Zirconium

Corrosion and oxidation of unalloyed zirconium in high-temperature water and steam are found to be irregular.^{13,14} This behavior is probably caused by variations in the content of impurities in the metal. Nitrogen and carbon impurities are particularly harmful. The oxidation rate of zirconium increases markedly when nitrogen and carbon concentrations exceed 40 and 300 ppm, respectively.^{15,16} Several zirconium alloys, including Zircaloy-2 and -4, are the most important alloys used in water-cooled nuclear reactors because they have the most reliable corrosion resistance in high-temperature water and steam. Zircaloy-2 is superior to unalloyed zirconium in high-temperature water and steam. A tightly adherent oxide film forms on this alloy at a rate that is at first quasi-cubic, but after an initial period the rate becomes linear. Unlike the oxide film on unalloyed zirconium, the oxide film on Zircaloy-2 remains dark and adherent throughout transition and in the post transition region. Figure 5 shows the normal rate of weight gain in water and steam for Zircaloy-4,¹⁷ which should be similar to that of Zircaloy-2.

Zircaloy-4 differs in composition from Zircaloy-2 in having no nickel and a slightly higher iron content. Both variations are intended to reduce hydrogen pickup in reactor operation, which will also be a requirement for ATW. Zircaloy-4 and -2 have close corrosion resistance. However, hydrogen pickup for Zircaloy-4 is significantly lower, particularly when the alloy is exposed to water at 360°C. At this temperature, hydrogen pickup for Zircaloy-4 is about 25% of theoretical, or less than half that for Zircaloy-2. In addition, hydrogen pickup for Zircaloy-4 is less sensitive to hydrogen overpressure than that of Zircaloy-2. For both zircaloys, hydrogen pickup is markedly decreased when dissolved oxygen is present in the corrosion medium.¹³

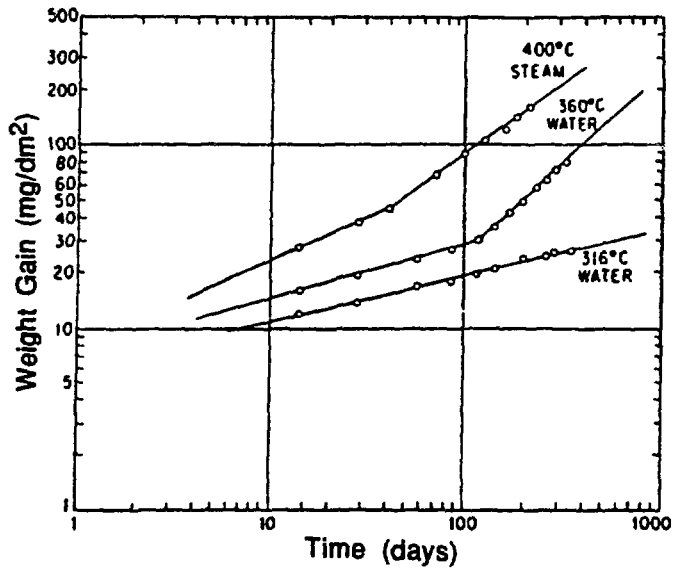


Fig. 5. Corrosion behavior of Zircaloy-4 in water and steam.

Other zirconium alloys that have been available since the early 1980s are a series known as Zircadyne zirconium alloys 702, 704, 705, and 706. While all of these alloys list 4.5% hafnium, they can be obtained as reactor grade (Hf < 100 ppm) quality.¹⁵ Zircadyne 702 is the most widely used in the chemical processing industry. This grade has the best overall corrosion resistance but is the lowest in strength of the Zircadyne alloys. Zircadyne 705 exhibits similar corrosion resistance to 702 in most environments, but has a significant strength advantage. Zircadyne 705's strength is nearly double that of 702. Zircadyne 705 also exhibits better formability than 702. Its strength levels often make it the most economical choice for construction of vessel walls. Both Zircadyne 702 and 705 are approved for use in the construction of vessels, according to the ASM Engineers Boiler and Pressure Vessel Code, Section VIII.

Many early process industry applications for zirconium used 704, a Zircadyne alloy containing tin, iron, and chromium, that is similar to nuclear grade Zircadyne alloys, which were designed for high-temperature, high-pressure water and steam environments. The corrosion resistance of Zircadyne 704 is comparable to unalloyed Zircadyne 702 in most chemical environments and is superior in high-temperature, high-pressure water and steam. The tensile strength of Zircadyne 704 is intermediate between that of 702 and 705. The chemistry and physical properties data on zirconium alloys are given in Appendix D.

Low-Alloy Carbon Steels

The corrosion resistance of carbon steel is dependent on the formation of an oxide surface film. However, resistance to corrosion is limited. Low alloy carbon steel is little affected by neutral water and is quite often used as container material for that reason. These steels may have some limited applications in an ATW design; however, the stainless steels are much better suited for corrosion applications.

Stainless Steels

Stainless steel is probably the most widely known and most commonly used material of construction for corrosion resistance. Stainless steel is not a singular material, as its name may imply, but rather a broad group of alloys, each of which exhibits its own physical and corrosion resistant properties. All the stainless steels can be divided into three basic groups:

- austenitic, gamma-face centered cubic (γ -fcc);
- ferritic, alpha-body centered cubic (α -bcc); and
- martensitic, alpha prime-body centered tetragonal (α' -bct).

Austenitic stainless steels contain both nickel and chromium. The addition of substitutional quantities of nickel to high chromium alloys stabilizes the austenite at room temperature. High nickel and chromium alloys in and around the spallation target are undesirable because of radiation activation of these elements, though they may be used elsewhere in the system, or isotopically tailored. The chemistry and physical properties of austenitic alloys are given in Appendix E. The corrosion resistance of the austenitic stainless steels is quite exceptional in water.

Ferritic stainless steels do not contain nickel but have generally higher chromium with a low carbon content. This is to stabilize the low-temperature alpha phase. The chemical and physical properties of ferritic alloys are given in Appendix E. The corrosion resistance of the ferritic stainless steels is rated good, but not as good as in the austenitic alloys.

Martensitic stainless steels contain moderate amounts of chromium, controlled amounts of carbon, and other additions. The chemistry and physical properties of some of the martensitic alloys are given in Appendix E. The corrosion resistance of martensitic stainless steels is inferior to that of the austenitic and many of the ferritic alloys. Generally, these alloys are not used in corrosive media, including water.

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APPENDIX A

Corrosion Issues

CONTENTS

- Introduction
 - General Corrosion
 - Localized Corrosion
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- Discussion of Corrosion Problems in Liquid Metals

INTRODUCTION

This appendix delineates some present and/or future issues, by providing a short overview on corrosion and corrosion resistance for metals. As defined in a broad sense, corrosion is the result of a chemical or electrochemical reaction between a material and its environment. Corrosion in metals is caused by a flow of electricity from one metal to another metal or a recipient of some kind. A moist conductor or an electrolyte must be present for this flow of energy to take place. The presence of an electrolyte is a key condition for the process of corrosion to occur. This reaction often results in the formation of a corrosion product—for example, rust on iron. However corrosion products need not be visible, and weight loss of the parent metal need not be appreciable. Corrosion also may occur in other forms, such as cracking or loss of strength or ductility. The five basic forms of corrosion are each classified by external appearance or by mechanism of attack. The form of the corrosion can vary widely, depending on the material and exposure conditions.

General Corrosion

General corrosion is dominated by uniform thinning and can include rusting of iron, tarnishing of silver, and high-temperature oxidation of metals. This type of corrosion is not unusual in metals because of their homogeneous structure. It is a surface phenomenon. Uniform corrosion is measured by metal penetration or weight loss of metal (excluding any adherent or nonadherent corrosion products) per unit time. Common units for measuring rate of uniform corrosion include mm/yr, mil/yr, or in./yr. These corrosion data represent time-averaged values. Depth of penetration is not proportional to time; corrosion occurs more rapidly at initial exposure than after prolonged exposure. For this reason, duration time should always be given when corrosion rates are reported.

Localized Corrosion

The damage caused by this kind of attack occurs in localized areas rather than uniformly over the exposed surface. The two main types of localized corrosion are crevice corrosion and pitting.

Crevice corrosion occurs when part of a metal surface is shielded or restricted and the remainder of the surface is exposed to a large volume of electrolyte. Shielding produces a change in the local environment, thus initiating attack in the shielded area. For this reason, crevice corrosion is also called concentration-cell corrosion.

Pitting produces sites of corrosive attack that are very small relative to the size of the entire exposed surface and can result in the rapid perforation of the metal sections. Pitting severity is sometimes expressed in terms of a pitting factor—the ratio of deepest penetration to average metal penetration. A pitting factor of one thus represents uniform attack.

These two forms of localized attack propagate by similar mechanisms, but they can be distinguished in the initiation phase. Crevice corrosion is initiated by the formation of a concentration cell, whereas pitting is initiated as a result of metallurgical discontinuities. These may include discontinuities in a protective film or coating or in compositional variations such as inclusions.

Galvanic Corrosion

Galvanic corrosion, also known as bimetal or dissimilar-metal corrosion, occurs when a metal or alloy is electrically coupled to another metal or alloy in the presence of an electrolyte. The less corrosion-resistant metal becomes the anode of a corrosion cell and is

attacked at an accelerated rate, while the more resistant material is protected. Galvanic corrosion is used to advantage in some cathodic protection systems, which employ sacrificial anodes to prevent or minimize corrosion of the structure being protected.

Several methods are used to minimize the effects of galvanic corrosion. Materials having similar corrosion potentials can be selected, the materials can be electrically insulated from each other, or the bimetallic component can be designed to have a larger ratio of anode/cathode area.

Dealloying (Preferential Corrosion)

Dealloying is the type of corrosion that occurs when one or more components of an alloy corrode preferentially. A porous residue is left behind that may retain the original shape of the alloy but has virtually no mechanical strength. Dealloying is caused by the difference in corrosion potentials in an alloy. The more noble element acts as the cathode in a galvanic cell, whereas the other, more active element becomes the anode and is attacked at an accelerated rate. The most common form of dealloying is dezincification of brass. An example of dezincification can be found in brass pipes. Dezincified brass pipe often retains enough strength to withstand water pressure until it is subjected to additional stress from water hammer or by an attempt to uncouple the pipe. Copper-based alloys containing aluminum also may suffer corrosion attack that resembles dezincification. In this situation aluminum corrodes preferentially.

Intergranular Corrosion

Intergranular corrosion occurs when grain boundaries are attacked preferentially because of the presence of precipitates or segregates in these areas. The grain-boundary precipitates are anodic to the large grain areas, resulting in rapid attack at the grain boundaries and possible catastrophic fracture. One of the most common examples of intergranular corrosion is as-welded or improperly heat-treated austenitic stainless steels. Elevated temperature exposure can result in grain boundary precipitation of carbides and/or intermetallic compounds in these materials; severe intergranular attack ensues on exposure to a corrosive environment. This phenomenon, known as sensitization, can be avoided or minimized by using low carbon or stabilized austenitic grades.

ENVIRONMENTAL STRESS CRACKING

Stress corrosion results from any mechanism that will generate high stress concentration in the presence of conditions conducive to corrosion. Thus, the effect of the stress is to accelerate the corrosion process rather than initiate it. Environmental stress cracking is the failure of a metal as a result of exposure to a combination of stress and corrosive environment. When the stress is cyclical, cracking occurs as a result of corrosion fatigue. Cracking in the presence of a sustained tensile stress is termed stress-corrosion cracking.

All metals can undergo mechanical fatigue. The fatigue strength (or fatigue life at a particular maximum stress value) of a metal always decreases in a corrosive environment. The effect varies depending on the metal/ environment combination. Stress corrosion cracking is a complex phenomenon that affects almost all metals in some environment. Cracking can be transgranular or intergranular. The tensile stress required to initiate and propagate stress corrosion cracks can be small and can be either externally applied or result from residual internal stress. Stress corrosion cracking almost always occurs in alloys; pure metals, although not immune, crack infrequently.

CORROSION SUSCEPTIBILITY

Because so many different metals must meet strength, weight, fatigue life, and other application requirements, corrosion resistance to a particular environment often determines the final selection of a specific metal or alloy. When no metal offers an "ideal" combination of mechanical performance and corrosion resistance, a less desirable metal may be used with some form of protection. Corrosion protection methods include inhibitors added to the corrosive medium, organic coatings, sacrificial coatings (galvanizing for example), cathodic or anodic protection, or barrier coatings (such as thermal spray coatings or chromium plating). Cladding materials offer protection that combines a low-cost base metal with a more resistant facing material.

GENERIC CORROSION INFORMATION ON SELECTED MATERIALS

Stainless Steels

Stainless steels were developed as corrosion-resistant substitutes for carbon and low-alloy steels. The stainless steels can be divided into five basic groups: austenitic, martensitic, ferritic, precipitation-hardenable, and duplex. Each group offers varying degrees of mechanical performance and corrosion resistance.

The most commonly used types of stainless steels are the austenitic 304 and 316. Both alloys contain 18% chromium and 8% nickel; in type 316, resistance is enhanced by addition of 2% to 3% molybdenum.

Martensitic stainless steels combine high strength with adequate toughness and corrosion resistance. Martensitic steels use relatively low chromium and carbon contents in combination with nitrogen, nickel, and molybdenum additions to achieve corrosion resistance.

Ferritic stainless steels incorporate chromium as high as 30% to achieve excellent corrosion resistance in seawater. Most ferritic grades are also highly resistant to chloride stress corrosion cracking.

Precipitation-hardenable stainless steels are nickel-chromium grades hardened by aging at elevated temperature. They have corrosion resistance comparable to the austenitic stainless steels.

Duplex stainless steels have microstructures of mixed ferrite and austenite. They combine high strength, good toughness, and good resistance to general corrosion and chloride environment stress corrosion cracking.

Nickel and High-Nickel Alloys

Nickel has outstanding resistance to hot or cold alkali solutions. Nickel resists stress corrosion cracking in most chloride environments, but is susceptible in caustic environments under certain conditions. Corrosion tests should be long in duration if accurate corrosion rates are to be obtained because a passive oxide film forms on nickel, initially protecting the surface from corrosion. Alloying nickel with 30% to 33% copper produces an alloy with properties similar to these of pure nickel but with improved resistance in nonoxidizing acids. Copper additions also allow handling of seawater and brackish waters and good performance at high fluid velocities. Nickel molybdenum alloys have significant corrosion resistance in reducing environments. Resistance to localized attack also is improved by the addition of molybdenum, which imparts strength to alloys designed for high-temperature service. Nickel-chromium alloys resist corrosive atmospheres at elevated temperatures. Depending on the specific alloy, they can be readily fabricated and welded; can be used in air at temperatures to 1100°C; provide good corrosion resistance against sulfuric acid; provide excellent high-temperature strength; and resist aqueous corrosion.

Copper and Its Alloys

Copper is highly corrosion resistant. It is especially resistant in most industrial, marine, and urban atmospheres, as well as in water and seawater. High thermal and electrical conductivity add to its versatility. Copper lacks strength, however, and is often alloyed with zinc, aluminum, tin, or nickel to improve mechanical properties. Copper-zinc alloys (brasses) are the most widely used copper alloys. Aqueous corrosion resistance below 15% zinc is good; if zinc is added to copper in concentrations near or greater than 15%, however, dezincification may occur in some environments. Small additions of tin ($\cong 1\%$) can alleviate this problem to some degree. High zinc alloys resist sulfide environments better than do low zinc brasses.

Copper-tin alloys (phosphor bronzes) contain phosphorus to impart oxidation resistance to the copper-tin base. They are among the oldest alloys known. Artifacts that have survived thousands of years of exposure to a variety of atmospheres, waters, and soils attest to the corrosion resistance of these phosphor bronzes. Corrosion performance (particularly dealloying resistance) of copper-aluminum alloys depends on their microstructure. All alpha, single-phase alloys have better corrosion resistance than duplex alpha-beta alloys. Aluminum bronzes generally resist corrosion in nonoxidizing mineral acids and many organic acids. Copper-nickel alloys are most widely used in saltwater service and have excellent resistance to bifouling and stress corrosion cracking. Copper-nickel alloys containing 10% to 30% nickel are extensively used for condenser tubes and heat exchanger tubes in recirculating steam systems.

Aluminum Alloys

Aluminum is a reactive metal that forms a strong, tightly adherent oxide film that is stable in neutral and acid solutions but is attacked by alkalies. Aluminum-magnesium alloys have good corrosion resistance and are used in a variety of building products, chemical processing equipment, and in applications involving exposure to seawater. Heat-treatable aluminum-copper alloys (2000 and 7000 series) have lower resistance to general corrosion than do alloys that do not contain copper. All 7000-series alloys are more resistant to general corrosion than are 2000-series alloys but are less resistant than alloys of other groups.

Tantalum

Tantalum is inert to practically all organic and inorganic compounds at temperatures below 150°C. Exceptions are hydrofluoric acid and fuming sulfuric acids. At temperatures below 150°C, tantalum is inert to all concentrations of hydrochloric and nitric acids, 98% sulfuric acid, 85% phosphoric acid, and a long list of common fluids. Conversely, any acid medium containing fluoride ions, except chromium plating baths, will rapidly attack tantalum. Hot oxalic acid is the only organic acid known to attack tantalum.

Zirconium

Zirconium is resistant to mineral acids, molten alkalis, alkaline solutions, and most organic and salt solutions. It has excellent oxidation resistance in air, steam, CO₂, SO₂, N₂, and O₂ at temperatures to 400°C. Zirconium's excellent corrosion resistance depends on the integrity of an inert, passive oxide film that forms on exposure to air. Zirconium is attacked by hydrofluoric acid, wet chlorine, concentrated sulfuric acid, aqua regia, and ferric chloride and cupric chloride solutions.

DISCUSSION OF CORROSION PROBLEMS IN LIQUID METALS

As discussed earlier, corrosion by its definition denotes the transfer of electrons. But this is not the case in liquid metal attack. The destruction of a solid metal by a liquid metal must by definition be broadened to allow for the solution or solubility of a solid metal in a liquid metal wherein no transfer of electrons is involved.

Liquid metal corrosion depends for the most part simply on the solution rate and the extent of solubility of the solid metal in the liquid metal. Note that many complicating factors can influence the solution rate or the attainment of the solubility limit. The formation of surface intermetallic compounds and of oxide or nitride films are good examples of such factors. In addition, impurities in the liquid metal can increase the solution rate. Additionally, other factors include temperature gradients and multimetallic systems that can cause an increase in the amount of attack over that expected to saturate the liquid metal, because of the mass transfer of material under the driving force of the temperature gradient or the concentration gradient.

Much attention has been given to the corrosion characteristics of liquid metals over a relatively short time. Several types of corrosive attacks of metals by liquid metals have been observed. The categories in which the mechanisms of liquid metal corrosion can be classified are as follows:

- solution attack,
- direct alloying,
- intergranular penetration,
- corrosion : by contaminants (impurity reactions),
- thermal-gradient transfer,
- concentration-gradient transfer, and
- corrosion-erosion.

In addition, several other variables affect liquid metal corrosion, including the following:

- temperature,
- temperature gradient,
- cyclic temperature fluctuation,
- surface area to volume ratio,
- purity of liquid metal,
- flow velocity,
- surface condition of container material,
- number of materials in contact with the same liquid metal, and
- microstructural state of the container material.

Following is a brief discussion of the above variables by types of corrosive attack.

Temperature is one of the most important variables. The higher the temperature, the higher the solubility of the solid metal in the liquid metal. Also, as the temperature increases, diffusion rates increase, a factor that is quite important in certain types of liquid metal corrosion.

When a temperature gradient exists in a liquid metal system, the difference in solubility of the dissolved metal between the hot and cold parts of the system gives rise to temperature-gradient mass transfer.

The cyclic temperature fluctuation is helpful in explaining erroneous static corrosion results. In a supposedly isothermal condition in a poorly controlled furnace, the liquid metal/solid metal interface temperature can fluctuate quite appreciably around a mean temperature. Thus, at the high temperature, material goes into solution and subsequently at the lower temperature comes out of solution and precipitates in the bulk liquid, or forms dendrites, or forms a uniform layer on the container wall.

The ratio of surface area of the solid metal to the volume of liquid metal is a controlling factor in the amount of corrosion experienced in a solid metal container in a static system inasmuch as the metal will corrode sufficiently to saturate the liquid metal at the operating temperature. Therefore, as the ratio of the surface area to volume decreases, the amount of corrosion increases.

Purity of the liquid metal can have a marked effect on the rate at which the solubility limit is reached and can markedly affect the corrosion rates. In ATW, this process may pose a significant problem.

The flow velocity (Reynolds number) is important in a forced circulation pump loop only in that a decrease in the thickness of the lamellar layer in the hot and cold legs occurs as the flow velocity increases. Thus, when metal atoms pass from the hot leg to the cold leg, the diffusion paths are shorter in these two regions.

The surface condition of the container material is not a particularly important variable; an equilibrium is reached between the liquid metal and the solid metal is reached rather quickly.

When two or more solid metals are in contact with a liquid metal, the phenomenon of dissimilar metal mass transfer, or concentration mass transfer, should be considered even when the temperature is constant. Equilibrium is attained in a multicomponent, multiphase system only when the chemical potential of each component in any given phase is equal to its chemical potential in every other phase. A redistribution of the components between the phases of the system, therefore, will tend to occur until the condition of the equilibrium of the chemical potentials has been satisfied. Thus, the driving force for this process is associated with the equalization of the chemical potentials and results in a decrease of the free energy of the system.

The condition of the container material, with respect to grain size and other variables, must be considered because the wettability of individual grains differs from the wettability of grain boundaries. A continuous carbide or oxide network at the grain boundary can greatly increase the corrosion that will be experienced. Alloys are more susceptible to this increase.

If all the phase diagrams of liquid metal–solid metal systems were available, we could ascertain the depth of attack that would occur in a static system as a result of simple solution by examining the solubility limit of the solid metal in the liquid metal at the operating temperature. We would have no conception, however, of the rate at which the solubility was achieved. Thus, after examining the iron-lead phase diagram we would expect that the amount of attack of iron by lead should be zero up to 1000°C in a static isothermal system. Corrosion tests have essentially confirmed this. Therefore, in a simple solution type attack, the amount of damage the solid metal will receive depends on the ratio of metallic surface area to the liquid volume of the system, but the rate at which the attack occurs can be influenced greatly by other factors, such as impurities in the system, which ATW will have as a result of daughter production.

We also need to evaluate the alloying that occurs between liquid metals and solid metals, particularly in long duration exposures of up to 30 years, such as those in an ATW environment. For such alloying to result, there must be some solubility of the liquid metal in the solid metal, e.g., copper-lead. In some systems, the liquid metal dissolves considerably in the solid metal and an intermetallic compound is formed. For example, when vanadium was tested in liquid lead at 100°C for 400 hours, an intermetallic compound was formed. When type 446 stainless steel was tested under similar conditions, the lead diffused into the alloy predominantly at the grain boundaries and formed a compound.

One of the more serious types of corrosion that can occur is that of deep intergranular penetration brought about by the selective removal of one constituent from an alloy. The best example of this is the selective removal of nickel from austenitic stainless steel. A considerable portion of the attack is attributed to the removal of nickel caused by the alloying of the nickel with lead at the higher temperature and depositing on the colder (less soluble) container wall.

In liquid metals, impurities such as oxygen, nitrogen, and even carbon can have an appreciable effect upon the rate of attack, as evidenced from past reactor experiments. In some cases the whole mode of attack can be changed because of the effect of the impurity on the surface tension or because of the reactivity of the impurity. An example of this is to be found in the attack of stainless steel by lithium when nitrogen is the principle contaminant.

The most damaging type of liquid metal corrosion is temperature-gradient mass transfer. Removal of a slight amount of a container wall will not adversely affect its load-carrying abilities; however, the collection of this material as scale or dendritic crystals (observed in past experiments) in the colder regions of heat exchanger tubes causes a cessation of flow. For example, mass-transferred material has been observed in which a plug of crystals was found in a type 446 stainless steel thermal convection loop that operated 200 hours at 800°C with a temperature gradient of 200°C.

The last type of liquid metal corrosion to be discussed here is dissimilar metal mass transfer, or gradient mass transfer. Conceptually, the manner in which dissimilar metal mass transfer takes place between two metals, A and B, and a liquid metal can be described. Atoms of metal A go into solution (must have some solubility) and move to the surface of metal B, either by diffusion and/or by the movement of the liquid. When they reach the surface of metal B, they come out of solution, alloy with metal B, and diffuse inward. The driving force for dissimilar metal transfer is the decrease in the free energy that is achieved through the alloying of the two metals. The greater the difference

between the chemical potentials of A and B in the two solid phases, the greater will be the driving force for the occurrence of mass transfer. The rate of mass transfer is dependent on the temperature, inasmuch as an increase in temperature will increase the diffusion rate in both the liquid and the solid phases. A high solubility of metal A in B (or B in A, or both) also will facilitate this type of mass transfer. Obviously, to avoid this situation, we should construct the metal loop system from same material.

APPENDIX B

Properties of Aluminum Alloys

Table B-I. Nominal Chemical Compositions of Representative Aluminum Wrought Alloys.

Alloy	Si	Cu	Mn	Mg	Cr	Zn	Ti	V	Zr
Non-heat-treatable alloys									
1060	99.60% min.	A							
1100	99.00% min.	A							
1350	99.50% min.	A							
3003		0.12	1.2						
3004			1.2	1.0					
5052				2.5	0.25				
5454			0.8	2.7	0.12				
5456			0.8	5.1	0.12				
5083			0.7	4.4	0.15				
5086			0.45	4.0	0.15				
7072 ^a						1.0			
Heat-treatable alloys									
2014	0.8	4.4	0.8	0.50			0.06	0.10	0.18
2219		6.3	0.30						
2024		4.4	0.6	1.5					
6061	0.6	0.28		1.0	0.20				
6063	0.4			0.7					
7005			0.45	1.4	0.13	4.5	0.04		0.14
7050		2.3		2.2		6.2			
7075		1.6		2.5	0.23	5.6			

^aCladding for Alclad products.

Table B-II. Typical Tensile Properties of Representative Non-Heat-Treatable Aluminum Wrought Alloys of Various Tempers.^a

Alloy and temper	Strength (MPa)		Elongation (%)	
	Ultimate	Yield	In 50 mm ^b	In 5D ^c
1060 -O	70	30	43	
-H12	85	75	16	
-H14	100	90	12	
-H16	115	105	8	
-H18	130	125	6	
1100 -O	90	35	35	42
-H14	125	125	9	18
-H18	165	150	5	13
3003 -O	110	40	30	37
-H14	150	145	8	14
-H18	200	185	4	9
3004 -O	180	70	20	22
-H34	240	200	9	10
-H38	285	250	5	5
5052 -O	195	90	25	27
-H34	260	215	10	12
-H38	290	255	7	7
5454 -O	250	115	22	
-H32	275	205	10	
-H34	305	240	10	
-H111	260	180	14	
-H112	250	125	18	
5456 -O	310	160		22
-H111	325	230		16
-H112	310	165		20
-H116, H321	350	255		14
5083 -O	290	145		20
-H116, H321	315	230		14
5086 -O	260	115	22	
-H116, H32	290	205	12	
-H34	325	255	10	
-H112	270	130	14	

^aAverages for various sizes, product forms, and methods of manufacture; not to be specified as engineering requirements or used for design purposes.

^b1.60-mm-thick specimen.

^c12.5-mm-diameter specimen.

Table B-III. Typical Tensile Properties of Representative Heat-Treatable Aluminum Wrought Alloys of Various Tempers.^a

Alloy and temper	Strength (MPa)		Elongation (%)	
	Ultimate	Yield	In 50 mm ^b	In 5D ^c
2014 -O	185	95		16
-T4, T451	425	290		18
-T6, T651	485	415		11
2219 -O	170	75	18	
-T37	395	315	11	
-T87	475	395	10	
2024 -O	185	75	20	20
-T4, T351	470	325	20	17
-T851	480	450	6	
-T86	515	490	6	7
6061 -O	125	55	25	27
-T4, T451	240	145	22	22
-T6, T651	310	275	12	15
6063 -O	90	50		
-T5	185	145	12	
-T6	240	215	12	
-T83	255	240	9	
7005 -O	195	85		20
-T63, T6351	370	315		11
7050 -T76, T7651	540	485		10
-T736, T73651	510	455		10
7075 -O	230	105	17	14
-T6, T651	570	505	11	9
-T76, T7651	535	470		10
-T73, T7351	500	435		11

^aAverages for various sizes, product forms, and methods of manufacture; not to be specified as engineering requirements or used for design purposes.

^b1.60-mm-thick specimen.

^c12.5-mm-diameter specimen.

**Table B-IV. Properties of Aluminum Alloy 6061.²
(1.0% Mg, 0.6% Si, 0.25% Cu, 0.25% Cr)**

ASTM numbers. B209, B210, B211, B221, B234, B235, B241, B247, B308, B313, and B316.

Government numbers. Alloy 6061, QQ-A-270, QQ-A-325, QQ-A-327, QQ-A-367, and WW-T-789.

Other designations. SAE 244 and 281; AMS 4021,4022, 4023, 4025, 4026, 4027, 4079, 4080, 4081,4082, 4083, 4115, 4116, 4117, 4126, 4127, 4150, 4160, and 4161.

Typical uses. Applications where good strength, formability, weldability, and very good resistance to corrosion are required. Aircraft landing mats, pontoon boats, canoes, furniture, vacuum cleaner tubing, bridge railings, marine applications, piping, welded assemblies, and transportation equipment are typical.

Density at 68°F (20°C). 2.70 g/cm³ (0.098 lb/in.3).

Liquidus temperature. 1200°F (649° C).

Solidus temperature. 1080°F (582°C).

Thermal expansion, micro-in./in./°C.

-76 to +68°F (-60 to +20°C)	21.8
68 to 212°F (20 to 100°C)	23.4
68 to 392°F (20 to 200°C)	24.3
68 to 572°F (20 to 300°C)	25.4

Specific heat at 212°F (100°C) is 0.23 cal/g.

Thermal conductivity at 77°F (25°C), cal/sq. cm/cm²/°C/sec. 0.41, O temper; 0.37, T4 and T6 tempers.

Electrical volume conductivity. 45% IACS, O temper; 40% IACS, T4 and T6 tempers.

Electrical resistivity at 68°F (20°C), mohm-cm. 3.83, O temper; 4.31, T4 and T6 tempers.

Electrolytic solution potential versus N/10 calomel electrode is 0.80 Volt, T4, temper; 0.83 volt, T6 temper (53 g NaCl + 3 g H₂O₂ solution).

Mechanical properties. See Tables B-V and B-VI, and Figs. B-1, B-2. Modulus of rigidity (bare products), 3,750,000 psi; Poisson's ratio, 0.33; shear yield strength, approximately 0.55 times the tensile yield strength.

Directional properties (all tempers of sheet). Tensile strength and elongation are approximately equal in the longitudinal and transverse directions.

Radiography. Same as for 1100 alloy.

Chemical composition limits. 0.8 to 1.2 Mg, 0.40 to 0.8 Si, 0.15 to 0.40 Cu, 0.15 to 0.35 Cr, 0.7 max Fe. 0.15 max Mn, 0.25 max Zn, 0.15 max Ti, 0.05 max each of other elements, total of which shall be 0.15 max, remainder Al.

Hot working temperature range. 500° to 950°F (260° to 510°C).

Heat treatment. see Table B-VII.

Table B-V. Typical Tensile Properties of 6061 Alloy at Various Temperatures When Heated for 10,000 Hours.²

Testing temp. (°F)	Tensile strength (psi)	Yield strength (psi)	Elongation (%)
BARE PRODUCTS			
O Temper			
5	18,000	8,000	30
300	16,000	8,000	30
400	9,000	6,500	55
500	5,500	4,000	70
600	4,000	2,500	85
700	3,000	2,000	95
T4 Temper			
75	35,000	21,000	25
300	30,000	21,000	25
400	19,000	15,000	28
500	7,500	5,000	60
600	4,500	2,500	85
700	3,000	2,000	95
T6 Temper			
75	45,000	40,000	17
300	34,000	31,000	20
400	19,000	15,000	28
500	7,500	5,000	60
600	4,500	2,500	85
700	3,000	2,000	95
CLAD PRODUCTS			
O Temper			
75	17,000	7,000	25
300	15,000	8,000	--
400	8,500	6,500	--
500	5,000	4,000	--
600	4,000	2,500	85
700	2,000	2,000	95
T4 Temper			
75	33,000	19,000	22
300	28,000	19,000	--
400	18,000	14,000	28
500	7,000	4,500	60
600	4,500	2,500	85
700	3,000	2,000	95
T6 Temper			
75	42,000	37,000	12
300	32,000	29,000	20
400	18,000	14,000	28
500	7,000	4,500	60
600	4,500	2,500	85
700	3,000	2,000	95

Table B-VI. Properties of Aluminum 6061.²

Temper	Tensile strength, psi(b)	Yield strength, psi(c)	Elongation, %		Hardness		Shear strength psi	Fatigue Limit psi(h)
			(d)	(e)	Rockwell(f)	Bhn (g)		
Bare Products								
O	18,000	8,000	25	30	H 60 to 75	30	12,000	9,000
T4	35,000	21,000	22	25	H 80 to 102	65	24,000	4,000
T6	45,000	40,000	12	17	E 85 to 97	95	30,000	4,000
Clad Products								
O	17,000	7,000	25	--	--	--	11,000	--
T4	33,000	19,000	22	--	--	--	22,000	--
T6	42,000	37,000	12	--	--	--	27,000	--

(a) These typical properties are average for various forms, size, and methods of manufacture and may not exactly describe any one particular product. Modulus of elasticity (average of tension and compression moduli) is 10,000,000 psi. Compression modulus is about 2% greater than tension modulus. (b) Strengths and elongations are unchanged or improved at low temperatures. (c) The compressive yield strength is approximately the same as the tensile yield strength. (d) Sheet specimen, 1/16 in. thick. (e) Round specimens, 1/2 in. in diameter. (f) Rockwell H 80 to 102 is equivalent to F 57 to 75; E 85 to 97 is equivalent to F 80 to 90. (g) 500-kg load, 10-mm ball. (h) Based on 500,000,000 cycles using R. R. Moore-type rotating-beam machine.

Table B-VII. Heat Treatment of 6061 Alloy.²

Purpose	Temperature		Time, hr.	Cooling
	°C	°F		
Complete annealing, O	413	775	2 to 3	Furnace cool to 500°F (50°F per hr max)
Removal of cold work	343	650	No holding time required	Not critical
Solution heat treatment, T4	516 to 543	960 to 1010	10 min to 1 hr in salt bath(a); longer time in air	Cold water quench
Precipitation, T6 (Start with T4 material)	174 to 179	345 to 355	6 to 10	Not critical

(a) Time at temperature depends on product and thickness. Longer times may be required for heavy sections and forgings.

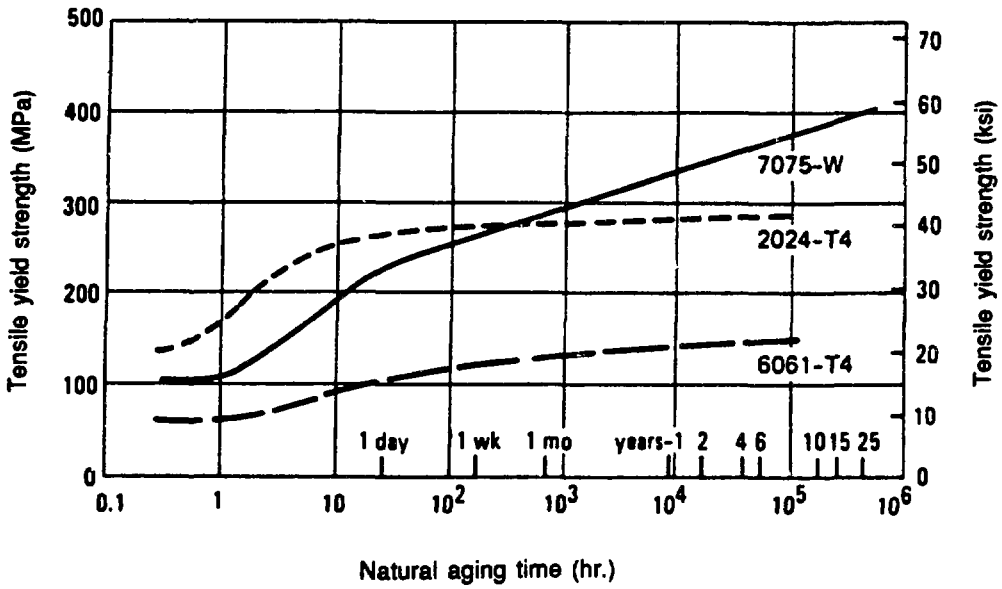


Fig. B-1. Natural aging curves for three-solution heat-treated wrought aluminum alloys.²

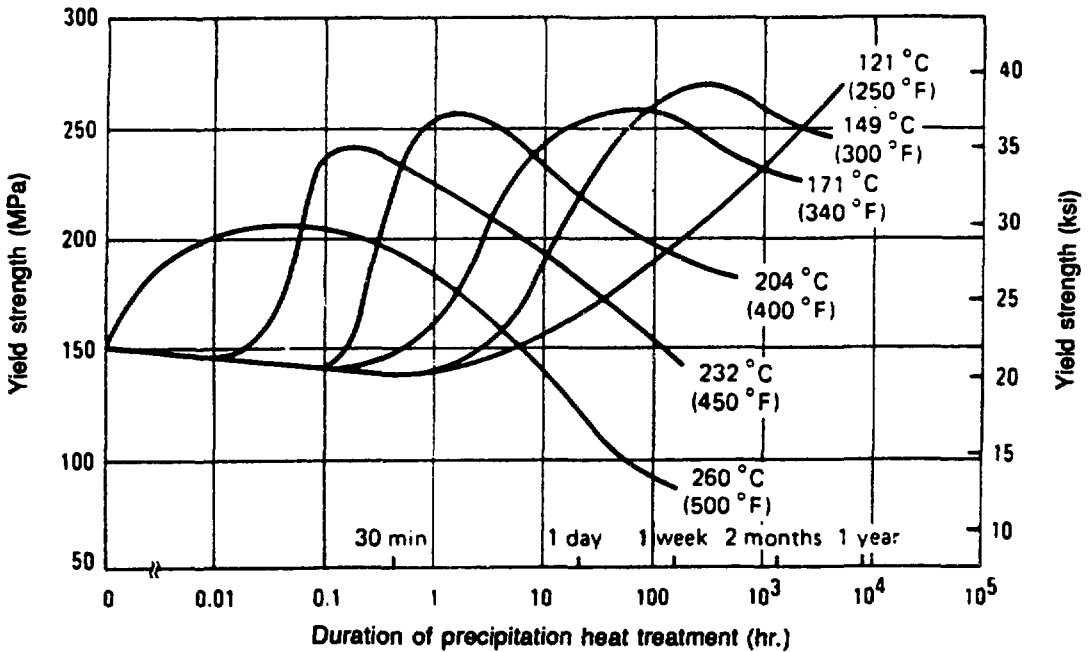


Fig. B-2. Precipitation heat treatment or artificial aging curves for solution heat-treated aluminum alloy 6061.²

APPENDIX C

Inconel 718

Inconel 718 is a nickel-base alloy recommended for high-temperature applications. It responds sluggishly to an age-hardening heat treatment that permits annealing and welding without spontaneous hardening during heating and cooling. It can be repair welded in the age-hardened condition. It has good ductility in the 650^o-760^oC temperature range along with high yield, creep, and rupture strength at temperatures up to 700^oC.

Inconel 718 is made age-hardenable by a niobium additions resulting in a precipitation of submicroscopic particles, presumed to be a nickel-niobium compound. For annealed material, optimum hardening occurs at 720^oC. This precipitation goes completely into solution at about 845^oC. In reference to dimensional stability, the alloy contracts slightly during the aging process, the linear contraction being about 0.05%.

Chemical and physical properties are given in Tables C-I through C-VIII.

Table C-I. Inconel 718 Composition.

Carbon	0.10 max.
Silicon	0.75 max.
Manganese	0.50 max.
Copper	0.75 max.
Nickel	50.0-55.0
Chromium	17.0-21.0
Niobium*	4.5-5.75
Molybdenum	2.8-3.3
Aluminum	0.2-1.0
Titanium	0.3-1.3
Iron	Remainder
*Plus incidental tantalum	

Table C-II. Physical Constants for Annealed Material.

Density gm/cm ³	8.19
Electrical resistivity, μohms/cm.....	127
Thermal coef. expansion/°C × 10 ⁻⁶	
24– 93°C.....	7.1
24– 427°C.....	7.9
24– 760°C.....	8.9
Modules of elasticity, psi (dynamic) × 10 ⁶	
at 20°C.....	29.6
at 538°C.....	25.5
at 760°C.....	23.1
at 955°C.....	11.1

Table C-III. Typical Mechanical Properties—Wrought.

	<u>Annealed</u>	<u>Annealed and Age-Hardened</u>
Tensile strength, psi	130,000	190,000
Yield strength, psi (0.2%)	60,000	150,000
Elongation, % in 2 in.	45	25

Table C-IV. Typical Mechanical Properties—Cast.

	<u>Cast and Age-Hardened</u>
Tensile strength, psi	145,000
Yield strength, psi (0.2%)	120,000
Elongation, % in 2 in.	10

**Table C-V. Effect of Cold Work on Elevated Temperature Properties
(20% Cold Rolled Sheet Aged 690°C for 1600 Hours).**

Test Temperature (°C)	Tensile Strength (psi)	Yield Strength (psi, 0.2%)	Elongation (% in 2 in.)
Room Temp.	210,000	188,000	9.5
93	204,000	184,000	9.0
204	198,000	180,000	8.5
316	192,000	175,000	8.0
427	186,000	172,000	7.5
538	180,000	170,000	7.5
650	183,000	160,000	8.0
760	132,000	122,000	11.0
816	90,000	80,000	20.0

**Table C-VI. Tensile Properties versus Temperature
(Mill Annealed Sheet, Aged 720°C for 16 Hours).**

Test Temperature (°C)	Tensile Strength (psi)	Yield Strength (psi, 0.2%)	Elongation (% in 2 in.)
Room Temp.	185,000	145,000	22
93	180,000	138,000	22
204	173,000	132,000	22
316	170,000	128,000	22
427	168,000	126,000	22
538	160,000	124,000	22
650	164,000	128,000	22(20)
760	120,000	104,000	26(9)
816	90,000	85,000	32(32)

(Heating at temperatures above 980°C, e.g., during annealing or furnace brazing, may reduce the elongation in the 650° to 815°C temperature range to the values indicated in parentheses.)

**Table C-VII. Tensile versus Compression Yield
Strength of Sheet
(Cold Rolled plus Age-Hardened).**

Tensile			Compression		
<u>.2% Yield</u>	<u>Tensile</u>	<u>% El</u>	<u>.02% Yield</u>	<u>0.2%</u>	<u>E × 10⁶</u>
171,500	1194,000	17.5	158,500	184,000	28.5

**Table C-VIII. Tensile versus Compression Yield
Strength of Sheet
(Annealed plus Age-Hardened).**

Tensile			Compression		
<u>.2% Yield</u>	<u>Tensile</u>	<u>% El</u>	<u>.02% Yield</u>	<u>0.2%</u>	<u>E × 10⁶</u>
141,000	181,000	20.0	158,500	152,000	28.0

APPENDIX D

Chemical, Physical, and Mechanical Properties of Zirconium Alloys

Table D-I. Chemical Properties of Zirconium Alloys.^{14,16}

Chemical Compositions of Zircadyne® Zirconium Alloys				
Grade (UNS No.)	Zircadyne 702 (R60702)	Zircadyne 704 (R60704)	Zircadyne 705 (R60705)	Zircadyne 706 (R60706)
Chemical Compositions, Weight, Percent				
Zr + Hf, min	99.2	97.5	95.5	95.5
Hafnium, max	4.5	4.5	4.5	4.5
Fe + Cr	0.2 max.	0.2-0.4	0.2 max.	0.2 max.
Tin	—	1.0-2.0	—	—
Hydrogen, max	0.005	0.005	0.005	0.005
Nitrogen, max.	0.025	0.025	0.025	0.025
Carbon, max.	0.05	0.05	0.05	0.05
Niobium (Columbium)	—	—	2.0-3.0	2.0-3.0
Oxygen, max.	0.16	0.18	0.18	0.16

Table D-II. Physical Properties of Zirconium Alloys.^{14,16}

Minimum ASTM Requirements for the Properties of Zircadyne® Zirconium at Room Temperature (Cold Worked and Annealed)				
Zircadyne Grade (UNS No.)	Zircadyne 702 (R60702)	Zircadyne 704 (R60704)	Zircadyne 705 (R60705)	Zircadyne 706 (R60706)
Tensile Strength, Min. ksi (MPa)	55 (379)	60 (413)	80 (552)	74 (510)
Yield Strength, Min. ksi (MPa)	30 (207)	35 (241)	55 (379)	50 (345)
Elongation (0.2% offset) Min Percent	16	14	16	20
Bend Test Radius*	5T	5T	3T	2.5T

*Bend tests are not applicable to material over 0.187 in. (4.75 mm) in thickness.
T equals the thickness of the bend test sample.

Table D-III. Typical Physical and Mechanical Properties of Unalloyed Zircadyne 702 and Zircadyne 705.

Physical Properties	Zr 702	Zr 705
ATOMIC NUMBER	40	—
ATOMIC WEIGHT.....	91.22	—
ATOMIC RADIUS		
A° (Zero Charge).....	1.60-1.62	—
A° (+ 4 Charge).....	0.80-0.90	—
DENSITY		
(g/cc at 20°C).....	6.510	6.640
(lbs./cubic inch).....	0.235	0.240
CRYSTAL STRUCTURE		
Alpha Phase.....	Hexagonal Close-Packed (below 865°C)	—
Beta Phase.....	Body-Centered Cubic (above 865°C)	Body-Centered Cubic (above 854°C)
Alpha + Beta Phase.....	—	Hexagonal Close-Packed + Body-Centered Cubic (below 854°C)
MELTING POINT.....	1852°C (3365°F)	1840°C (3344°F)
BOILING POINT.....	4377°C (7910°F)	4380°C (7916°F)
COEFFICIENT OF THERMAL EXPANSION per °C		
25°C (73°F).....	5.89×10^{-6}	6.3×10^{-6}
THERMAL CONDUCTIVITY (300-800°K)		
BTU - ft./hr.-ft ² -°F.....	13	10
Watts/m.-°K.....	22	17.1
SPECIFIC HEAT [BTU/lb/°F (32°-212°F)].....	0.068	0.067
VAPOR PRESSURE (mm Hg)		
2000°C (3632°F).....	0.01	—
3600°C (6512°F).....	900.0	—
ELECTRICAL RESISTIVITY [Microhm-cm at 20°C, (68°F)].....	39.7	55.0
TEMPERATURE COEFFICIENT OF RESISTIVITY PER °C		
20°C (68°F).....	0.0044	—
LATENT HEAT OF FUSION (Cal/gm).....	60.4	—
LATENT HEAT OF VAPORIZATION (Cal/gm).....	1550	—
Mechanical Properties		
MODULUS OF ELASTICITY (psi).....	14.4×10^6	14.0×10^6
SHEAR MODULUS (psi).....	5.25×10^6	5.0×10^6
POISSON'S RATIO (Ambient Temperature).....	0.35	0.33

Table D-IV. Minimum ASTM Requirements for the Mechanical Properties of Zirconium at Room Temperature (Cold Worked and Annealed).

Zircadyne Grade (ASTM Designation)	Zircadyne 702 (R60702)	Zircadyne 704 (R60704)	Zircadyne 705 (R60705)	Zircadyne 706 (R60706)
Tensile Strength, Min. ksi (MPa)	55 (379)	60 (413)	80 (552)	74 (510)
Yield Strength, Min. ksi (MPa)	30 (207)	35 (241)	55 (379)	50 (345)
Elongation (0.2% offset) Min. Percent	16	14	16	20
Bend Test Radius*	5T	5T	3T	2.5T

*Bend tests are not applicable to material over 0.187 in. (4.75 mm) in thickness.
T equals the thickness of the bend test sample.

Table D-V. Densities of Zircadyne Zirconium.

	Zircadyne 702	Zircadyne 704	Zircadyne 705	Zircadyne 706
Density g/cc at 20°C	6.510	6.570	6.640	6.640
lbs./cubic inch	0.235	0.237	0.240	0.240

Table D-VI. ASME Mechanical Requirements of Zirconium Grade 702 and Grade 705 for Unfired Pressure Vessels.

Material Form and Spec. No.	Grade	Condition	Specified Tensile Strength Kips/Sq.in.	Minimum Yield Strength Kips/Sq.in.	Notes	Maximum Allowable Stress Values in Tension For Metal Temperature Not Exceeding °F						
						100	200	300	400	500	600	700
Flat Rolled Products SB 551	702		52.0	30.0		13.0	11.0	9.3	7.0	6.1	6.0	4.8
	705		80.0	55.0		20.0	16.6	14.2	12.5	11.3	10.4	9.9
Tubing SB 523	702	Seamless	52.0	30.0		13.0	11.0	9.3	7.0	6.1	6.0	4.8
	705	Seamless	80.0	55.0		20.0	16.6	14.2	12.5	11.3	10.4	9.9
Tubing SB 523	702	Welded	52.0	30.0	(1)(2)	11.1	9.4	7.9	6.0	5.2	5.1	4.1
	705	Welded	80.0	55.0	(1)(2)	17.0	14.1	12.0	10.6	9.6	8.5	7.6
Forgings SB 493	702		52.0	30.0		13.0	11.0	9.3	7.0	6.1	6.0	4.8
	705		80.0	55.0		20.0	16.6	14.2	12.5	11.3	10.4	9.9
Bar SB 550	702		52.0	30.0		13.0	11.0	9.3	7.0	6.1	6.0	4.8
	705		80.0	55.0		20.0	16.6	14.2	12.5	11.3	10.4	9.9

(1) 85 percent joint efficiency has been used in determining the allowable stress value for welded tube
(2) Filler metal shall not be used in the manufacture of welded tube.

High Temperature Properties of Zirconium and Zirconium alloys

Creep Strength. Creep, a time-dependent strain occurring under stress, is an important consideration when designing equipment for use at high temperatures. Creep rate is usually expressed as percent plastic deformation for a given time period at a constant load. Creep is important in applications where close tolerances are required and exposure to high temperatures occurs.

Figures D-1 to D-3 shows typical tensile properties versus temperature for Zircadyne 702, 704 and 705. Figures D-4 and D-5 show creep rate versus stress for Zircadyne 702 and 705.

Stress Rupture. Stress rupture testing is a method of determining the life of a metal under a constant load at a constant temperature. Stress rupture is generally used as a design criterion for alloys subjected to loads which may produce failure in a short period of time.

Figures D-6 and D-7 show the stress rupture curves for Zircadyne 702 and 705.

Low Temperature Properties. There is no low temperature ductile-to-brittle transition with zirconium or zirconium alloys.

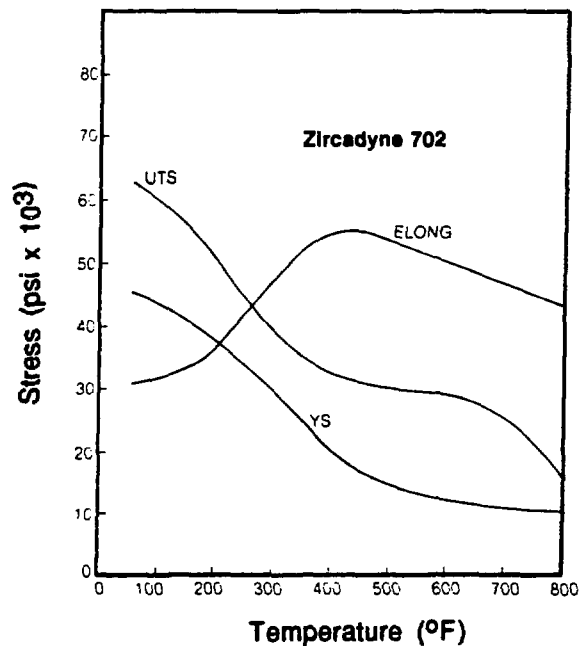


Fig. D-1. Typical tensile properties of unalloyed Zircadyne 702.

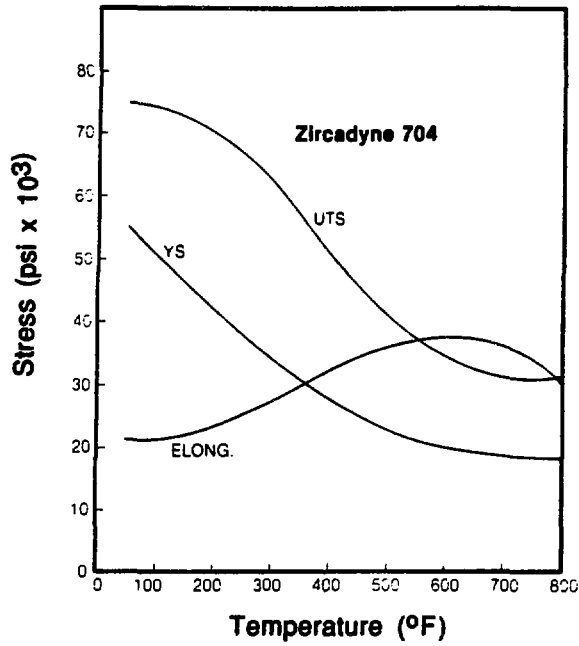


Fig. D-2. Typical tensile properties of Zircadyne 704.

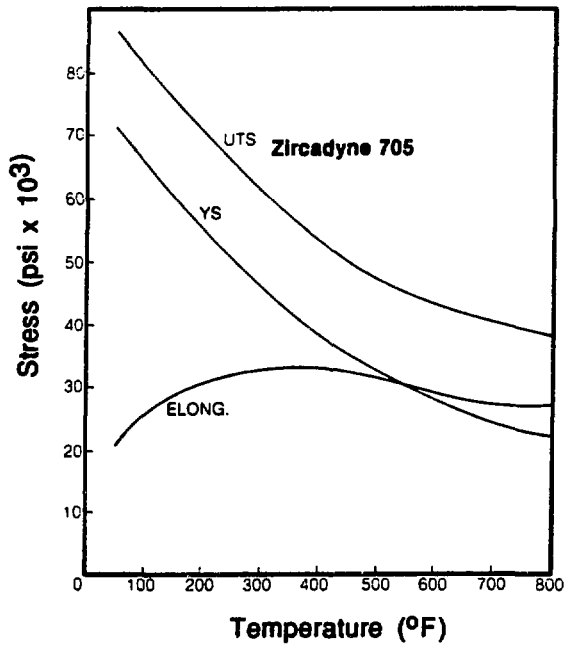


Fig. D-3. Typical tensile properties of Zircadyne 705.

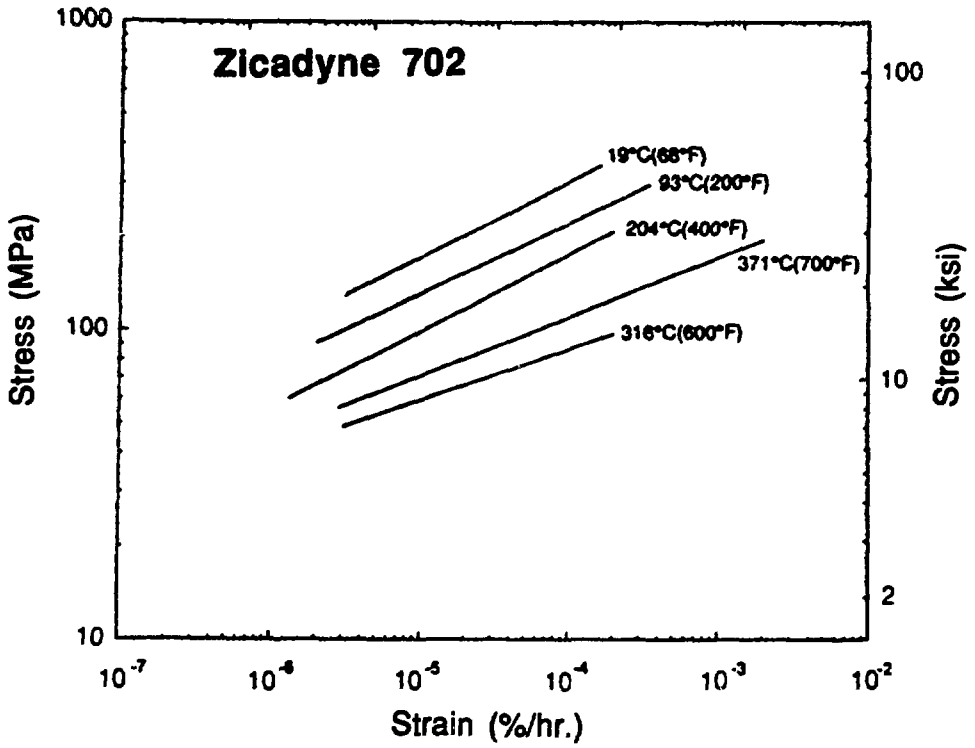


Fig. D-4. Zircadyne 702 minimum creep rate versus stress.

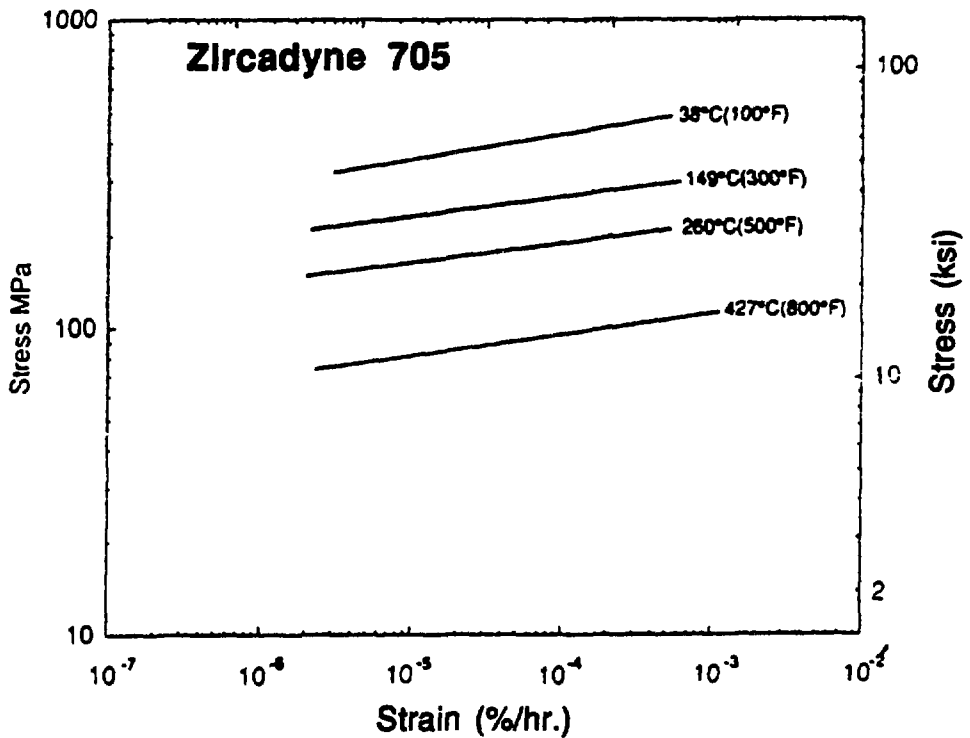


Fig. D-5. Zircadyne 705 minimum creep rate versus stress.

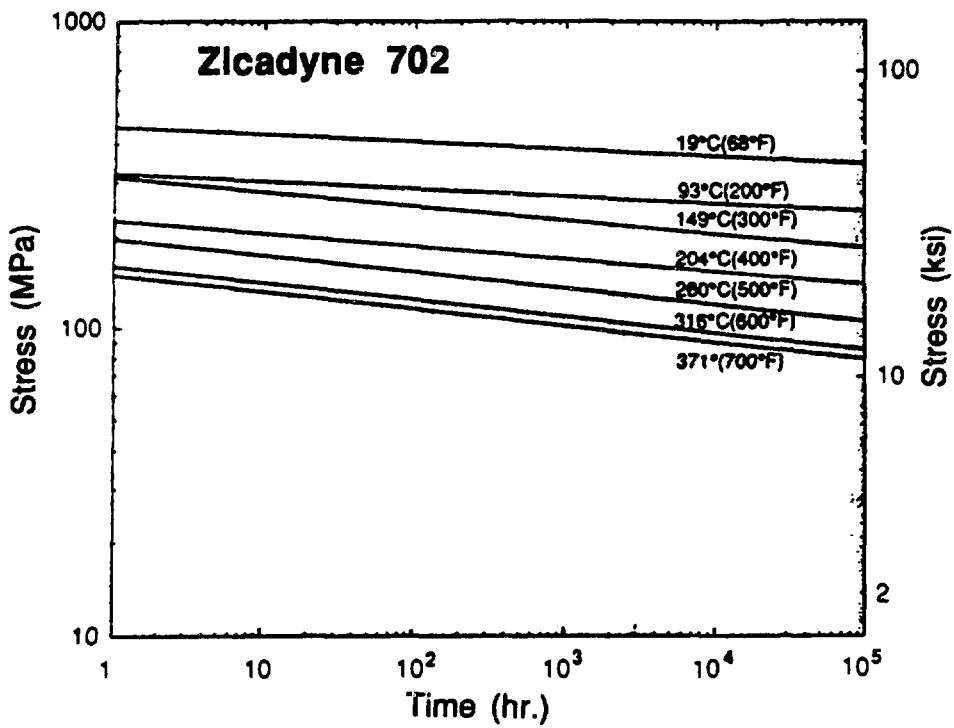


Fig. D-6. Zircadyne 702 stress-rupture curves.

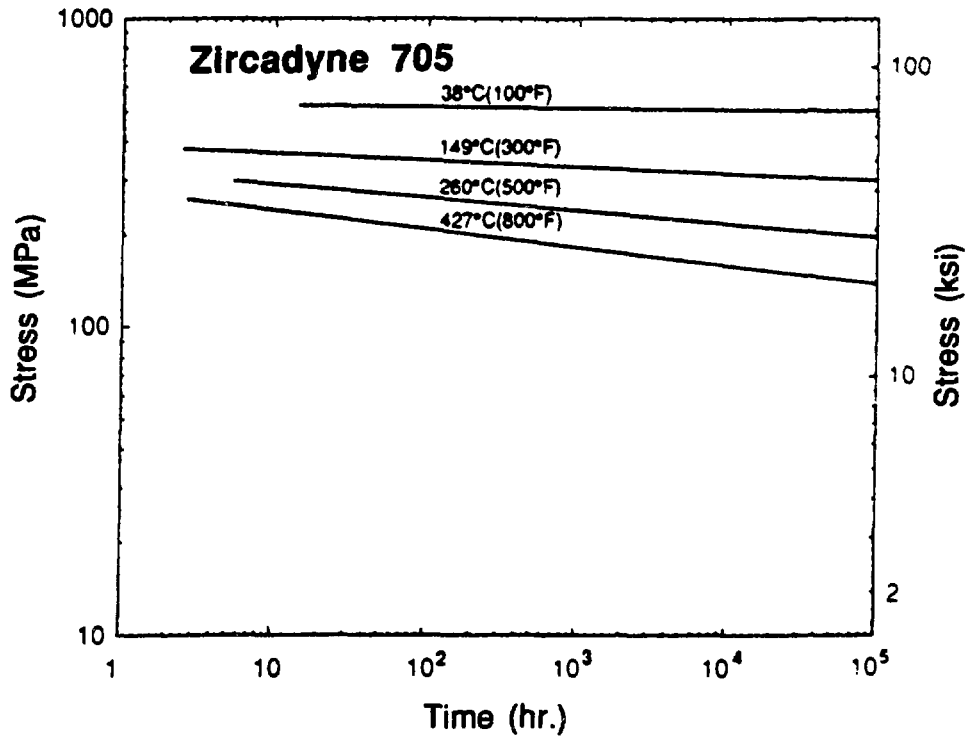


Fig. D-7. Zircadyne 705 stress-rupture curves.

Fatigue in Zircadyne and Zircadyne Alloys. Zircadyne and its alloys exhibit a fatigue limit behavior (stress below which failure will not occur) similar to most ferrous alloys. At ambient temperatures, however, Zircadyne and its alloys exhibit somewhat higher strengths in the direction transverse to the rolling direction. This property of higher strengths in the transverse direction is unlike that of most ferrous alloys and is due to the orientation and directional properties of the hexagonal close-packed crystalline structure of alpha zirconium opposed to the body-centered cubic crystalline structure of alpha iron. This increased strength in the transverse direction is more significant at stresses above the fatigue limit.

The fatigue limit is increased by most alloy additions up to about 2.5 wt %. Oxygen, which is considered an alloying element in zirconium, has a very strong effect on the properties, although detailed fatigue data are available only to about 0.34 wt %. The following values for the fatigue limits are based on a minimum of 10 cycles.

The addition of metallic alloying elements increases the unnotched fatigue limit but has little effect on the notched fatigue limit. The fatigue limits are shown in Figure D-8 for notched and unnotched Zircadyne 702.

<u>Alloy</u>	<u>Fatigue Limit (psi)¹⁸</u>	
	<u>Unnotched</u>	<u>Notched</u>
Unalloyed Iodide Zr	21,000	8,000
Iodide Zr + 0.34 wt % O	56,000	12,000
Grade 704, annealed 2hr at 1350°F	41,000	8,000
Grade 705, aged 4 hr at 1050°F	42,000	8,000

Additional data on zircaloy alloys are given in Figures D-9 to D-17.

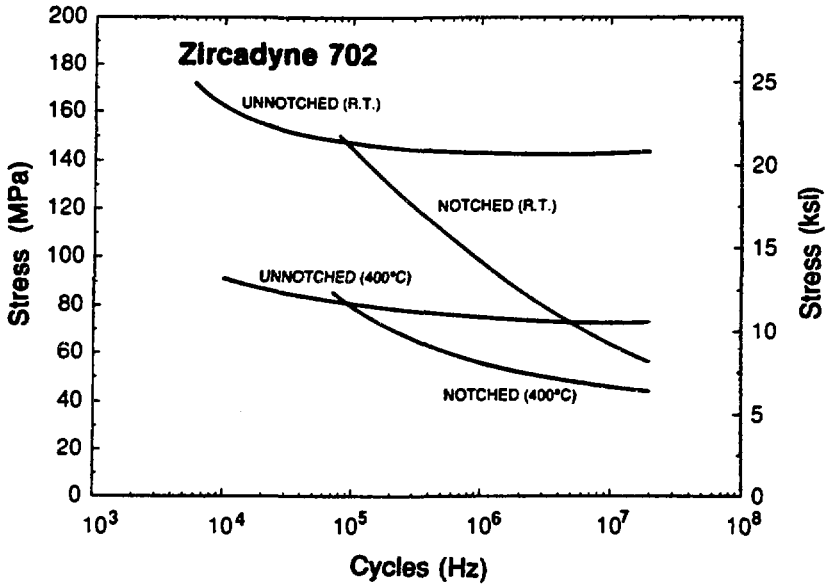


Fig. D-8. Fatigue limit for Zircadyne 702.¹⁴

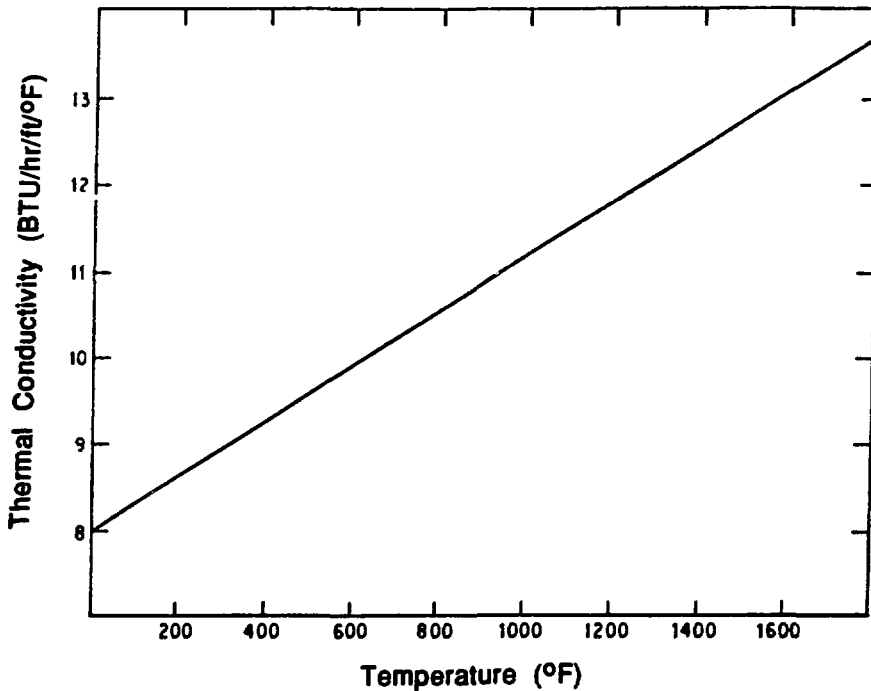


Fig. D-9. Thermal conductivity of Zircaloy-4 tubing.¹⁶

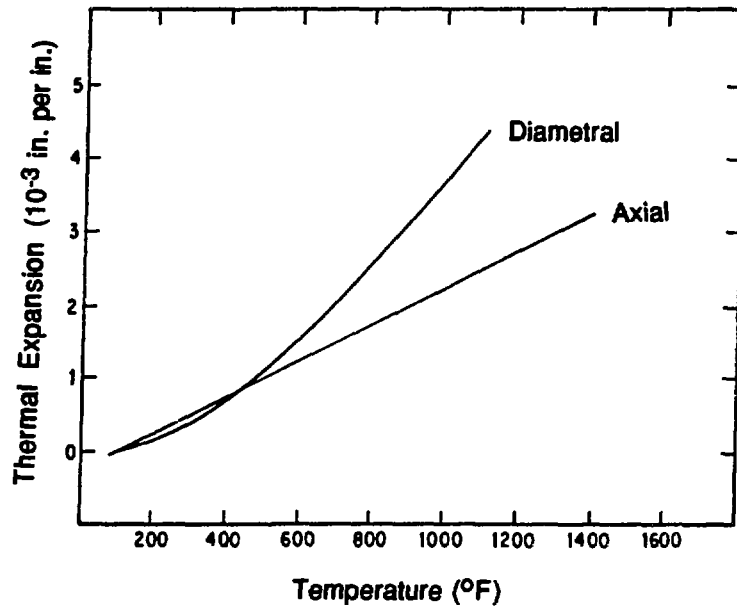


Fig. D-10. Thermal expansion of Zircaloy tubing.¹⁶

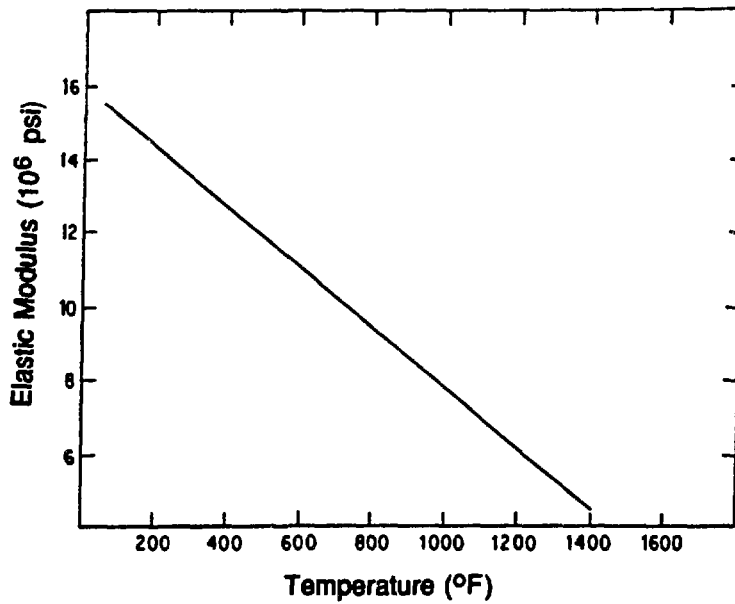


Fig. D-11. Static modulus of elasticity.¹⁶

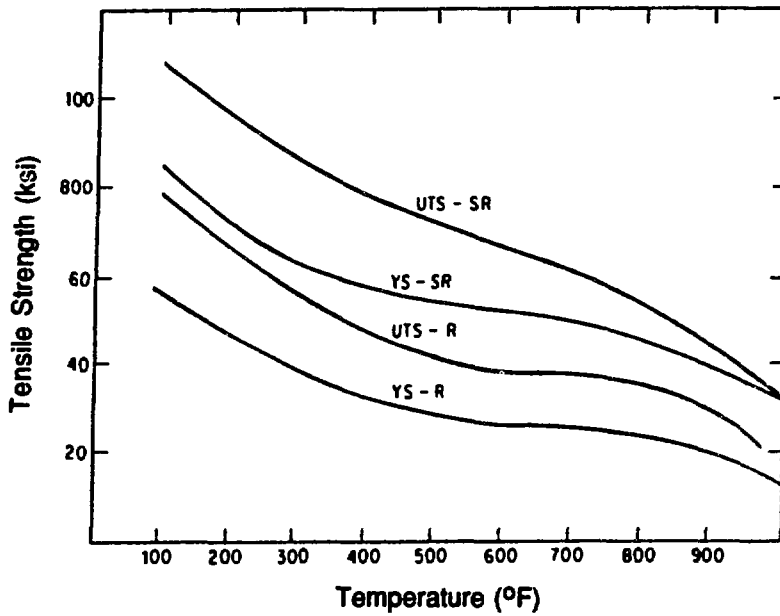


Fig. D-12. Tensile strength of Zircaloy tubing. Note: UTS—ultimate tensile strength, YS—yield strength, R—recrystallized, and SR—cold work and stress relieved.¹⁶

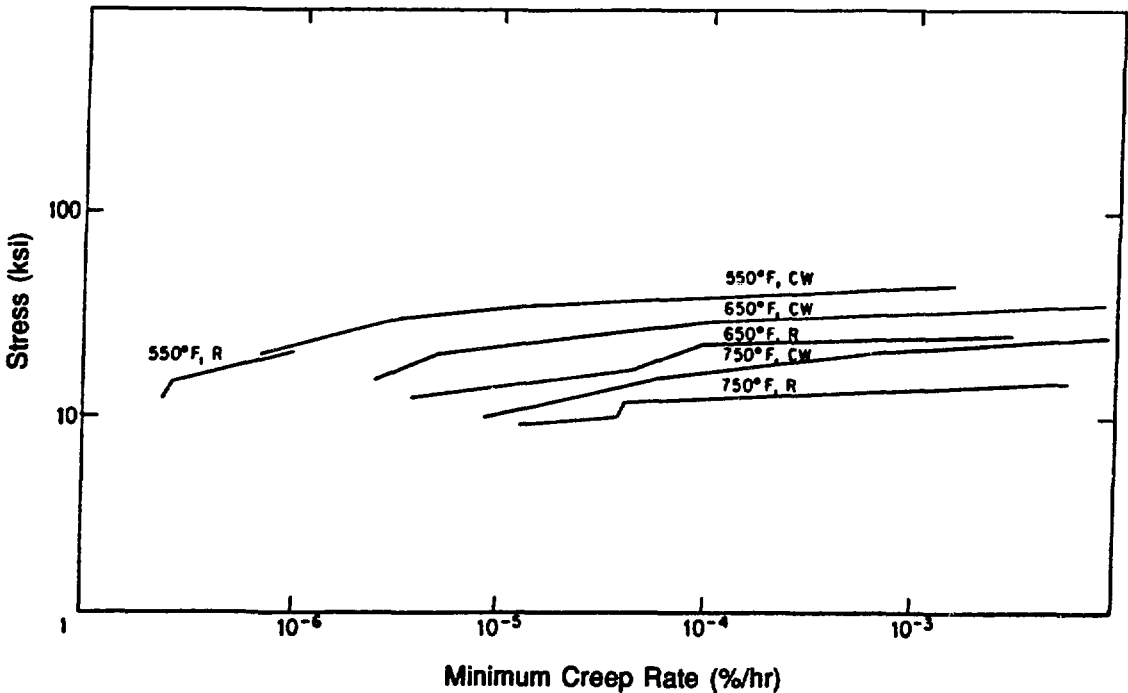


Fig. D-13. Creep rate for recrystallized (R) and 15% cold-worked (CW) Zircaloy-2 sheet. Temperature is temperature of test.¹⁶

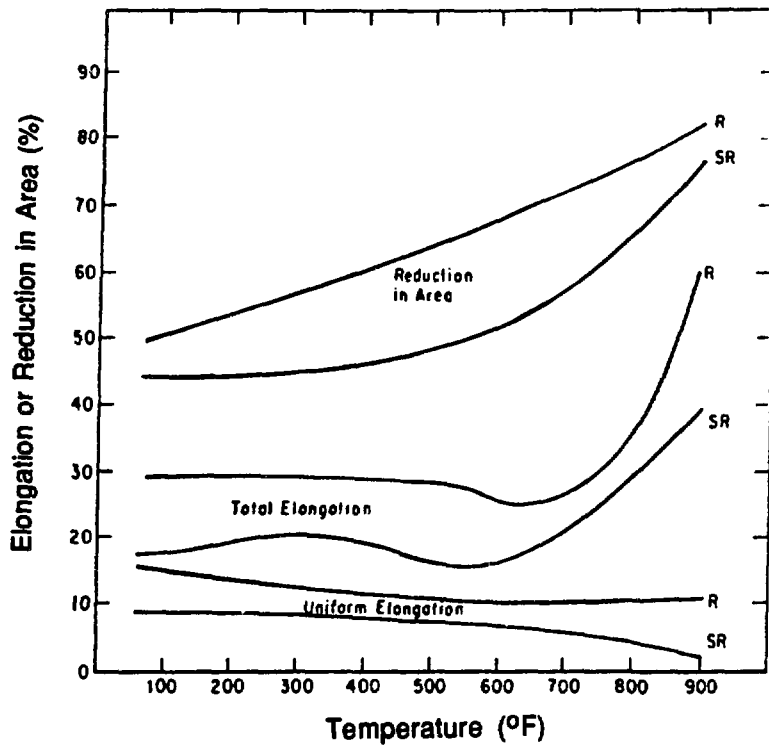


Fig. D-14. Tensile ductility of Zircaloy tubing.¹⁶

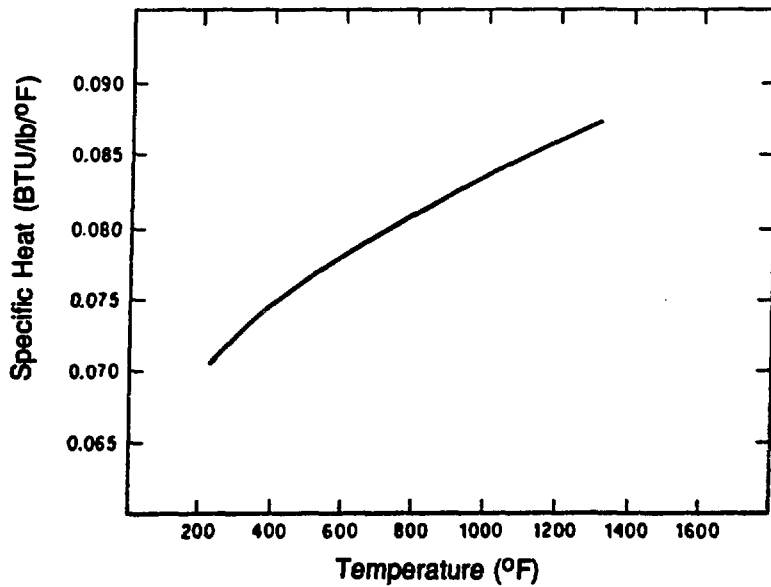


Fig. D-15. Specific heat of Zircaloy-2.¹⁶

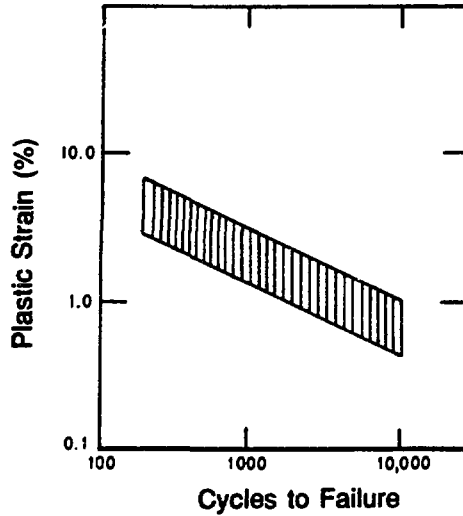


Fig. D-16. Fatigue data on cold-worked Zircaloy-2 tested at 572°F. Levels of cold work varied from 6% to 41%.¹⁶

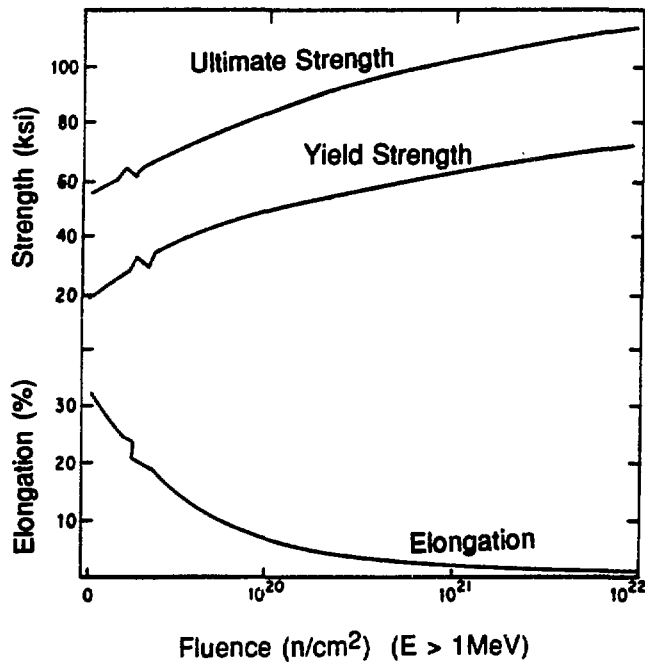


Fig. D-17. Effect of irradiation on tensile properties of annealed Zircaloy-2. Irradiated at 290°C in an experimental test reactor (ETR).¹⁶

APPENDIX E

Chemical, Physical, and Mechanical Properties of Various Steels

Table E-I. Chemical Composition of Austenitic Stainless Steels.¹⁵

AISI type	Nominal composition (%)					
	C max.	Mn max.	Si max.	Cr	Ni	Others ^B
201	0.15	7.5 ^b	1.00	16.00-8.00	3.50-5.50	0.25 max. N
202	0.15	10.00 ^c	1.00	17.00-19.00	4.00-6.00	0.25 max. N
205	0.25	15.50 ^d	0.50	16.50-18.00	1.00-1.75	0.32/0.4 max. N
301	0.15	2.00	1.00	16.00-18.00	6.00-8.00	
302	0.15	2.00	1.00	17.00-19.00	8.00-10.00	
302B	0.15	2.00	3.00 ^e	17.00-19.00	8.00-10.00	
303	0.15	2.00	1.00	17.00-19.00	8.00-10.00	0.15 min. S
303(Se)	0.15	2.00	1.00	17.00-19.00	8.00-10.00	0.15 min. Se
304	0.08	2.00	1.00	18.00-20.00	8.00-12.00	
304L	0.03	2.00	1.00	18.00-20.00	8.00-12.00	
304N	0.08	2.00	1.00	18.00-20.00	8.00-10.50	0.1/0.16 N
305	0.12	2.00	1.00	17.00-19.00	10.00-13.00	
308	0.08	2.00	1.00	19.00-21.00	10.00-12.00	
309	0.20	2.00	1.00	22.00-24.00	12.00-15.00	
309S	0.08	2.00	1.00	22.00-24.00	12.00-15.00	
310	0.25	2.00	1.50	24.00-26.00	19.00-22.00	
310S	0.08	2.00	1.50	24.00-26.00	19.00-22.00	
314	0.25	2.00	3.00 ^f	23.00-26.00	13.00-22.00	
316	0.08	2.00	1.00	16.00-18.00	10.00-14.00	2.00-3.00 Mo
316F	0.08	2.00	1.00	16.00-18.00	10.00-14.00	1.75-2.50 Mo
316L	0.03	2.00	1.00	16.00-18.00	10.00-14.00	2.00/3.00 Mo
316N	0.08	2.00	1.00	16.00-18.00	10.00-14.00	2.00-3.00 Mo
317	0.08	2.00	1.00	18.00-20.00	11.00-15.00	3.00-4.00 Mo
317L	0.03	2.00	1.00	18.00-20.00	11.00-15.00	3.00-4.00 Mo
321	0.08	2.00	1.00	17.00-19.00	9.00-12.00	5XC min Cb-Ta
330	0.08	2.00	1.50 ^g	17.00-20.00	34.00-37.00	0.10TA 0.20 Cb
347	0.08	2.00	1.00	17.00-19.00	9.00-13.00	10XC min. Cb-Ta
348	0.08	2.00	1.00	17.00-19.00	9.00-13.00	10C min. Cb-Ta 2.0 Mo
20Cb3	0.07	0.75	1.00	20.0	29.0	3.0 Cu
904L	0.02	—	—	21.0	25.5	8XC Min. Cb-Ta 4.7 Mo 1.5 Cu

^aOther elements in addition to those shown are as follows: Phosphorus is 0.03% max. in type 205; 0.06% max. in types 201 and 202; 0.045% max. in types 301, 302, 302B, 304, 304L, 304N, 305, 308, 309, 309S, 310, 310S, 314, 316, 316N, 316L, 317, 317L, 321, 330, 347, and 348; 0.20% max. in types 303, 303(Se), and 316D. Sulfur is 0.030% max. in types 201, 202, 205, 301, 302, 302B, 304, 304L, 304N, 305, 308, 309, 309S, 310, 310X, 314, 316, 316L, 316N, 317, 317L, 321, 330, 347, and 348; 0.15% min. in type 303; 0.10% min. in type 316D.

^bMn range 4.40 to 7.50.

^cMn range 7.50 to 10.00.

^dMn range 14.00 to 15.50.

^eSi range 2.00 to 3.00.

^fSi range 1.50 to 3.00.

Table E-II. Physical Properties of Austenitic Stainless Steels.¹⁵

Stain- less steel type	Form and condition	Hard- ness (Brinell)	Density (lb/in. ³)	Specific gravity	Melting point (°F)	Specific heat (32-212°F) (BTU/lb °F)	Thermal expansion coefficient (32-212°F) ($\times 10^{-6}$ in./in. °F)	Thermal conductivity (32-212°F) [BTU(ft)(hr) (°F/in.)]	Electrical resistivity (68°F) (Ω /cir mil)	Tensile modulus of elasticity ($\times 10^{10}$ lb)
201	Annealed	194	0.28	7.7	255-2650	0.12		113	414	28.6
202	Annealed	184	0.28	7.7	2550-2650	0.12		113	414	28.6
205	Annealed	217								
301	Annealed	160								
	Cold-rolled	186	0.29	8.02	2550-2590	0.12	9.4			
302	Annealed	160								
	Cold-rolled	Up to 400	0.29	8.02	2550-2590	0.12	9.6	112.8	435	28
302B	Annealed	165								
303	Annealed	165								
303(Se)	Annealed	160								
304	Annealed	160								
	Cold-rolled	Up to 400	0.29	8.02	2550-2650	0.12	9.6	113	435	28
304L	Annealed	150								
	Cold-rolled	277	0.29	8.02	2550-2650	0.12	9.6	113	435	28
304N	Annealed	160								
305	Annealed	156								
308	Annealed	150								
309	Annealed	165								
	Cold-rolled	275	0.29	8.02	2550-2650	0.12	8.3	96	470	29
309S	Annealed	165								
310	Annealed	165	0.29	8.02	2550-2650	0.12	8.0	96	470	29
310S	Annealed	170								
314S	Annealed	170								
316	Annealed	165								
	Cold-rolled	275	0.29	8.02	2500-2550	0.12	8.9	113	445	28
316F	Annealed									
316L	Annealed	150								
	Cold-drawn	275	0.29	8.02	2500-2550	0.12	8.9	113	445	28
316N	Annealed									
317	Annealed	160								
317L	Annealed	160								
321	Annealed	160								
	Cold-rolled	300	0.286	7.92	2550-2600	0.12	9.3	110	435	28
330	Annealed	156								
347	Annealed	160								
	Cold-rolled	300	0.286	7.92	2550-2600	0.12	9.3	110	435	28
348	Annealed	160								
20CB3	Annealed	160	0.289	8.02		0.12	8.6	145.2	451	28
904L	Annealed	140	0.288	7.9		0.105	8.4	94	480	28.4

Table E-III. Mechanical Properties of Austenitic Stainless Steels.¹⁵

Stainless steel type	Form and condition	Yield strength (0.2% offset) ($\times 10^6 \psi$)	Tensile strength ($\times 10^5 \psi$)	Elongation in 2 in. (%)
201	Annealed	55	115	55
202	Annealed	50	100	60
205	Annealed	69	120	58
301	Annealed	30	100	72
	Cold rolled ^a	Up to 165	Up to 200	15 ^b
302	Annealed	30	90	60
	Cold rolled ^a	Up to 165	Up to 190	8 ^b
302B	Annealed	40	95	50
	Cold rolled	Up to 160	Up to 185	
303	Annealed	35	90	50
303(Se)	Annealed	35	90	50
304	Annealed	30	85	62
	Cold rolled	Up to 160	Up to 185	8 ^b
304L	Annealed	30	80	60
	Cold drawn	95	125	25
304N	Annealed	48	90	50
305	Annealed	85	37	55
308	Annealed	85	35	55
309	Annealed	30	82	50
	Cold rolled	Up to 120	Up to 140	4 ^b
309S	Annealed	90	40	45
310	Annealed	40	100	50
310S	Annealed	95	40	45
314	Annealed	100	50	45
316	Annealed	30	90	50
	Cold rolled	Up to 120	Up to 150	8 ^b
316F	Annealed	38	85	60
316L	Annealed	30	80	60
	Cold drawn	60	90	45
316N	Annealed	48	90	45
317	Annealed	90	40	50
317L	Annealed	38	86	55
321	Annealed	30	85	50
	Cold rolled	Up to 120	Up to 150	5 ^b
330	Annealed	38	80	40
347	Annealed	30	85	50
	Cold rolled	Up to 120	Up to 150	5 ^b
348	Annealed	92	35	50
20Cb3		35	85	50
904L	Annealed	35	85	45

^aThe cold-rolled properties depend on composition; types 302 and 304 are not often rolled in excess of 175,000 ψ tensile strength

^bThe values for elongation (percentage in 2 in.) are obtainable in steel cold rolled to the *maximum* stated yield strength and tensile strength. For lower values of tensile strength, elongation will be correspondingly higher.

Table E-IV. Chemical Composition of Ferritic Stainless Steels.¹⁵

AISI type	Nominal Composition (%)				
	C max.	Mn max.	Si min.	Cr	Other ^a
405	0.08	1.00	1.00	11.50-14.50	0.10-0.30 Al
403	0.12	1.00	1.00	14.00-18.00	
430F	0.12	1.25	1.00	14.00-18.00	0.15 S min.
430 (Se)	0.12	1.25	1.00	14.00-18.00	0.15 Se min.
444	0.025	1.00	1.00 (max)	17.5-19.5	1.75-2.50 Mo
446	0.20	1.50	1.00	23.00-17.00	0.25 max. N

^aOther elements in addition to those shown are as follows: Phosphorus is 0.06% max. in types 430F and 430 (Se); sulfur is 0.030% max. in types 405, 430, 444, and 446; 0.15% min. in type 430F; nickel 1.00% max. in type 444; titanium + niobium 0.80% max. in type 444.

Table E-V. Physical Properties of Ferritic Stainless Steels.¹⁵

AISI type	Form and condition	Hardness (Brinell)	Density (lb/in. ³)	Specific gravity	Melting point (°F)	Specific heat (32-212°F) (BTU/lb °F)	Thermal expansion coefficient (32-212°F) ($\times 10^{-6}$ in./in. °F)	Thermal conductivity (32-212°F) [BTU/(in. ²)(hr) (°F/in.)]	Electrical resistivity (68°F) (Ω /cir mil)	Tensile modulus of elasticity ($\times 10^6 \psi$)
405	Annealed	150								
430	Annealed	165								
	Cold-rolled	225	0.28	7.75	2600-2750	0.11	6.0	180	360	29
430F	Annealed	170								
430(Se)	Annealed	170								
444	Annealed	217	0.28	7.75		0.102	6.1	186		
446	Annealed	165	0.27	7.45	2600-2750	0.12	5.8	145	405	29

Table E-VI. Mechanical Properties of Ferritic Stainless Steels.¹⁵

Stainless steel type	Form and condition	Yield strength (0.2% offset) ($\times 10^3 \psi$)	Tensile strength ($\times 10^3 \psi$)	Elongation in 2 in. (%)
405	Annealed	70	40	30
430	Annealed	75	45	30
	Cold drawn			
430F	Annealed	40	70	350
	Cold rolled	95	110	10
430(Se)	Annealed	80	55	25
444	Annealed	40	60	20
446	Annealed	50	80	30

Table E-VII. Chemical Composition of Martensitic Steels.¹⁵

AISI type	Nominal composition (%)					
	C	Mn max.	Si max.	Cr	Ni	Other ^a
403	0.15 max.	1.00	0.50	11.50-13.00		
410	0.15 max.	1.00	1.00	11.50-13.50		
414	0.15 max.	1.00	1.00	11.50-13.50	1.25-2.50	
416	0.15 max.	1.25	1.00	12.00-14.00		0.15 S min.
416(Se)	0.15 max.	1.25	1.00	12.00-14.00		0.15 S min.
420	0.15 min.	1.00	1.00	12.00-14.00		
431	0.20 max.	1.00	1.00	15.00-17.00	1.25-2.50	
440A	0.60-0.75	1.00	1.00	16.00-18.00		0.75 Mo max.
440B	0.75-0.95	1.00	1.00	16.00-18.00		0.75 Mo max.
440C	0.95-1.20	1.00	1.00	16.00-18.00		0.75 Mo max.
501	0.10 min.	1.00	1.00	4.00-6.00		0.40-0.65 Mo
502	1.10 max.	1.00	1.00	4.00-6.00		0.40-0.65 Mo

^aOther elements in addition to those shown are as follows: Phosphorus is 0.06% max. in types 416 and 416(Se); sulfur is 0.03% max. in types 403, 410, 414, 420, 431, 440A, 440B, 440C, 501, and 502.

Table E-VIII. Mechanical Properties of Martensitic Steels.¹⁵

Stainless steel type	Form and condition	Yield strength (0.2% offset) ($\times 10^3 \psi$)	Tensile strength ($\times 10^3 \psi$)	Elongation in 2 in. (%)
403	Annealed	75	40	30
410	Annealed	40	75	30
	Heat-treated	115	150	15
414	Annealed	80	100	22
	Heat-treated	150	200	17
416	Annealed	75	40	30
416(Se)	Annealed	75	40	30
420	Annealed	60	98	28
	Heat-treated	200	250	8
431	Annealed	85	120	25
	Heat-treated	150	196	20
440A	Annealed	105	60	20
440B	Annealed	107	62	18
440C	Annealed	110	65	13
501	Annealed	70	30	28
502	Annealed	70	30	30

Table E-IX. Physical Properties of Martensitic Steels.¹⁵

Stainless steel type	Form and condition	Hardness (Brinell)	Density (lb/in. ³)	Specific gravity	Melting point (°F)	Specific heat (32-212°F) (BTU/lb °F)	Thermal expansion coefficient (32-212°F) ($\times 10^{-6}$ in./in. °F)	Thermal conductivity (32-212°F) [BTU(ft ²)(hr) (°F/in.)]	Electrical resistivity (68°F) (Ω /cir mil)	Tensile modulus of elasticity ($\times 10^6 \psi$)
403	Annealed	155	0.28	7.75	2700-2790	0.11	5.5	173	340	29
	Heat-treated	410								
410	Annealed	150	0.28	7.75	2700-2790	0.11	5.5	173	340	29
	Heat-treated	410								
414	Annealed	217	0.28	7.75	2600-2700	0.11	6.1	173	420	29
	Heat-treated	387								
416	Annealed	155	0.28	7.75	2600-2700	0.11	6.1	173	420	29
	Heat-treated	410								
416(Se)	Annealed	155	0.28	7.75	2650-2750	0.11	5.7	173	330	29
	Heat-treated	410								
420	Annealed	180	0.28	7.75	2650-2750	0.11	5.7	173	330	29
	Heat-treated	480								
431	Annealed	250	0.28	7.75	2600-2700	0.11	6.5	140	430	29
	Heat-treated	400								
440	Annealed	215	0.28	7.75	2600-2700	0.11	6.5	140	430	29
	Heat-treated	570								
440B	Annealed	220	0.28	7.75	2600-2700	0.11	6.5	140	430	29
	Heat-treated	590								
440C	Annealed	230	0.28	7.75	2600-2700	0.11	6.5	140	430	29
	Heat-treated	610								
501	Annealed	160	0.28	7.75	2600-2700	0.11	6.5	140	430	29
502	Annealed	150								

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