HIGH-TEMPERATURE CHARACTERISTICS OF STAINLESS STEEL

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HIGH-TEMPERATURE CHARACTERISTICS OF STAINLESS STEEL

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The Nickel Institute republished the handbook in 2020. Despite the age of this publication the information herein is considered to be generally valid.

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CONTENTS

INTRODUCTION

Developments in pollution control, nuclear power, solar energy, coal gasification, gas turbines, and in all phases of industrial production involved with high-temperature service are causing designers to more-closely examine the elevated-temperature properties of construction materials. As new processes are commercialized, and as production capacities in existing facilities are increased, temperature often becomes an important consideration in the selection of materials.

Stainless steels are generally selected, first, on the basis of their resistance to corrosion and, second, on the basis of their mechanical properties. As the temperatures of operating environments increase, however, elevated-temperature properties quickly become the primary concern. The family of stainless steels is most versatile in its ability to meet the requirements of high-temperature service.

This booklet discusses factors that should be considered by engineers facing problems in designing equipment for high-temperature service. The characteristics that make some of the stainless steels particularly useful in high-temperature environments are described, and typical engineering data are presented. Also discussed, but as a secondary consideration, are the corrosion-resistance qualities of stainless steels at elevated temperatures.

It should be noted that the material presented in this booklet is intended as general information; for design purposes it is recommended that reference be made to appropriate standards and specifications, such as those prepared by the American Society of Mechanical Engineers (ASME) and the American Society for Testing and Materials (ASTM).

HIGH-TEMPERATURE DESIGN FACTORS

There are four design factors that engineers consider when choosing materials for service at elevated temperature. These design factors are:
1. Service life
2. Allowable deformation
3. Environment
4. Cost.

Service Life

The design service-life requirement of any given component or piece of equipment can vary from seconds in certain aerospace applications, such as rocket engines, to 25 or more years for power plant condenser tubes. Between these extremes are other more-moderate service-life requirements, such as those in chemical, petrochemical, or petroleum processing, where process design changes are more likely to occur at 10- to 15-year intervals.

Life expectancy may also vary from company to company within any given industry. For example, in thermal- cracking stills in the petroleum industry, some plants have standardized on Type 304 stainless steel, whereas, other plants with similar equipment and operating conditions use chromium-molybdenum steels with lower alloy contents. Naturally, the latter materials will not last as long as the former, but that is part of the design plan for those plants; i.e., low-cost materials but more frequent replacement versus more-expensive materials having longer service life.

For a given type of steel at a specific thickness, the expected service life depends on the maximum temperature to which it is exposed *plus* the maximum stresses to which it is subjected, also whether service is at a constant temperature or at intermittently high temperature.

For a prolonged service life, such as 20 years, plain carbon steels are usually limited to a maximum operating temperature of 750°F (399°C); the ½% molybdenum alloy steels to approximately 850°F (454°C); and the stainless steels to considerably higher temperatures depending upon the type used. It is important to recognize that for high-temperature service, strength at temperature is related to time at temperature.

Allowable Deformation

Another factor to consider in designing for high-temperature service is the amount of deformation that can be permitted during the total service life. This factor determines which of two high-temperature strength properties should be given priority; creep or creep-rupture (sometimes called stress-rupture). If the component is small and/or the tolerances very close, such as in turbine blades, creep is regarded as the overriding factor. But if the component is large and capable of accommodating greater deformation, such as shell-and-tube heat exchangers, the creep rupture strength is the usual basis for selection. Where considerable deformation is permitted, it is well to know the anticipated time to rupture, so parts can be scheduled for replacement before failure occurs. It is also useful to know whether or not service at elevated temperature is cyclic or continuous. Cyclic operation may lead to failure by fatigue or loss of metal due to flaking of the oxide scale prior to the expected creep-rupture time.

A discussion of the mechanical strength properties of stainless steels at elevated temperatures begins on page 5.

Environment

The effect of exposure of a material to media can be a very complex subject. Elevated temperatures tend to increase corrosive action, heat transfer may affect corrosivity, thermal cycling can increase metal wastage through spalling of protective scale on the metal surface, and metal temperature probably will not be the same as the environment to which it is exposed. Generally, if oxidation or other forms of scaling are expected to be severe, a greater cross-sectional area – beyond that indicated by mechanical-property requirements – is usually specified. Problems like this cannot be solved by laboratory analysis. It requires observation of test specimens in actual operating environments in pilot plants or full-size units.

A discussion of the corrosion behavior of stainless steels in various high-temperature environments begins on page 18.

Cost

The consideration of cost in selecting materials for high-temperature service must reflect not only the initial cost of the equipment but the cost of replacement and downtime as well. Designers should not rule out the more highly alloyed, more-costly materials if a premature

failure could result in shutting down the entire plant and loss of valuable production. Designers should consider the possibility of using different steels within the same application. For example, in tubular recuperators for preheating ingot soaking pit air, the combustion gas passes through tubes composed of lengths of Type 446, Type 430, and 5% chromium steel welded together. The combustion gas enters the Type 446 stainless steel end of the tube at 1600°F (871°C) and exits the 5% chromium steel end of the tube at 800°F (427°C).

CRITERIA FOR SELECTION

Once the design parameters have been established, the engineer may then evaluate the materials that appear to be capable of meeting the design strength requirements. For service at elevated temperatures, the first factor to be considered is hot strength, as this is decisive in determining the deformation over the expected life. Thermal stability is second, since this may set limits to a particular type from the standpoint of softening or, more commonly, embrittlement. Physical properties may also be significant in certain cases.

Short-Time Tensile Properties

Up to a temperature of about 900°F (482°C), the short-time tensile properties are most important. These are property values that can be used where parts are not exposed to high service temperatures for extended periods of time. The standard tests for these properties are conducted after the test specimens have been held at a temperature only long enough to insure uniform temperature throughout – normally about 30 minutes. The data do not reflect any effect of long-time exposure to high temperatures. The special techniques involved in performing the tension test at elevated temperatures are covered by ASTM Specifications E21 and E151.

For long-term service at temperatures about 900°F (482°C), design information is obtained from creep and creep-rupture tests. However, at temperatures above 1500°F (816°C), the short-time data are useful as a guide for hot-working operations.

Figure 1 illustrates a broad concept of the strength ranges being considered. As shown, the stainless steels have a higher hot strength than low-carbon unalloyed steel, with the austenitic (300 Series) grades displaying considerably higher

strengths than the martensitic or ferritic (400 Series) grades. The precipitation hardening grades show considerably higher hot strengths at lower temperatures, but their strength advantage disappears quickly as they begin to overage.

The strengthening of stainless steels by cold working or heat treatment can be beneficial in the temperature range where the steels behave in an elastic manner (up to about 900°F (482°C)). At higher temperatures this advantage is lost, as illustrated by the charts in Figures 2 and 3. Figure 2 shows the effect of cold work on the short-time tensile properties of Type 301, and in Figure 3, which shows typical short-time tensile strengths of various stainless steels, the advantage of using Type 410 in the quenched-and-

tempered condition can be seen. (Short-time tensile data on eight AISI-numbered stainless steels frequently used for high-temperature service are presented in the tables beginning on page 32.)

Creep

Over about 900°F (482°C), deformation under stress is plastic rather than elastic, so the yield point as determined by the short-time tensile test is higher than the creep or stress-rupture strength. Therefore, in structures operating at temperatures above 900°F (482°C), *time* becomes a major factor in determining safe loading stresses, since the stress which will cause failure or a maximum permissible elongation decreases directly as the time during which the

Figure 1
Hot-Strength Characteristics (1)

General comparison of the hot-strength characteristics of austenitic, martensitic and ferritic stainless steels with those of low-carbon unalloyed steel and semi-austenitic precipitation and transformation-hardening steels.
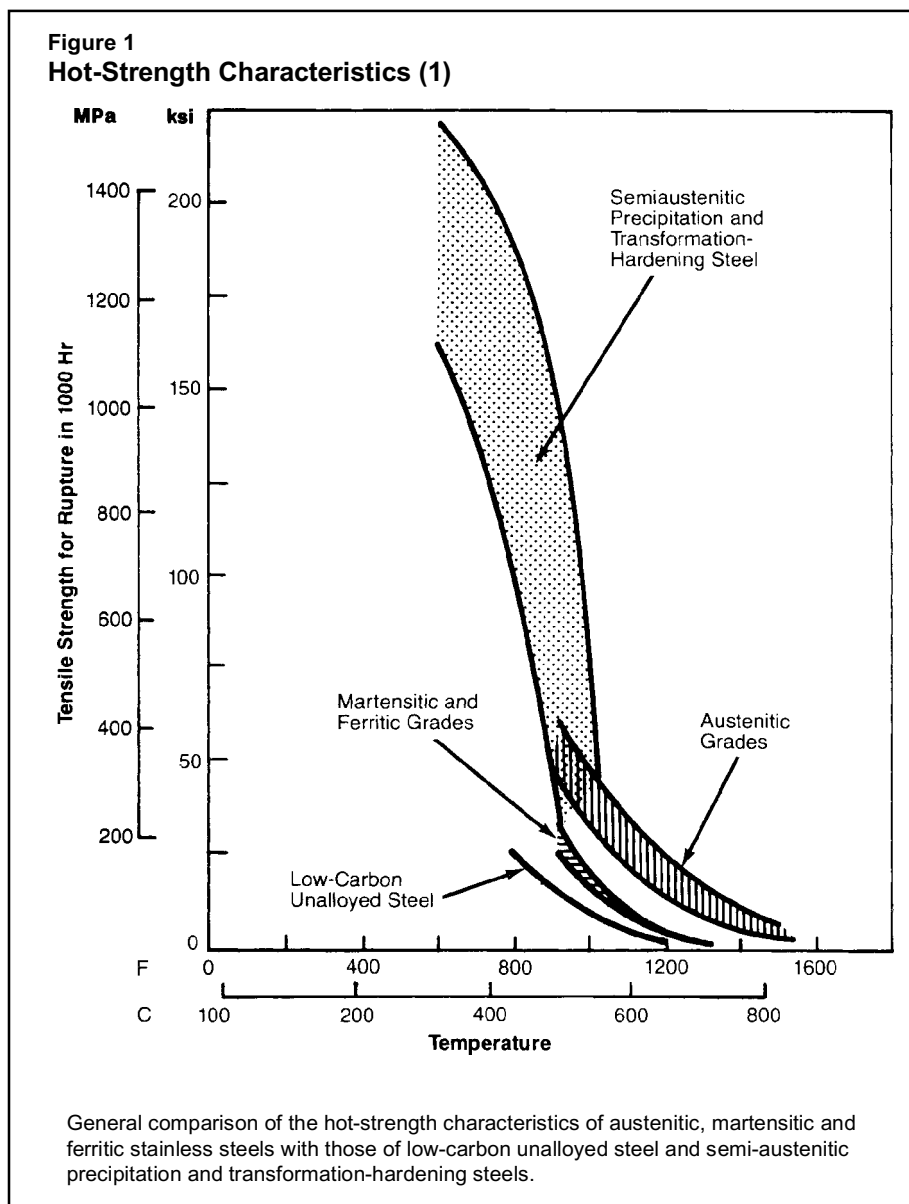
stress is applied.

The function of the creep test is to determine the creep rate and amount of deformation as a function of applied stress, time, and temperature. While the method of measuring creep is simple enough in principle, satisfactory results require precise control of furnace temperature, specimen alignment, and applied stress. The recommended practice for conducting creep tests is covered by ASTM Specification El 39.

When the change of length taking place in a specimen over a period of time is plotted against the elapsed time, a creep curve is obtained, such as illustrated in Figure 4. When the load is first applied, an initial elongation (A) occurs. Then the specimen strains gradually, at a decreasing creep rate during the primary stage of creep (B). The creep rate then becomes essentially constant for a period of time during the secondary or steady-state stage of creep (C). The slope of the creep curve in this second stage (which is also referred to as minimum-creep rate) is the rate commonly used for design purposes. Finally, if the time is long enough, the creep rate will increase (D), eventually leading to fracture of the specimen.

At the end of the test period, if fracture has not occured, the load is removed and elastic contraction (E) occurs, corresponding approximately to the elastic extension at the start of the test. Thus, it is apparent that metals creeping under stress at high temperature can and do show both plastic and elastic properties. The amount of permanent deformation is represented by (F).

Figure 4
Schematic Creep Curve (1)

A. Elastic Extension
B. Creep at Decreasing Rate
C. Creep at Approximately Constant Rate
D. Creep at Increasing Rate
E. Elastic Contraction
F. Permanent Change of Length
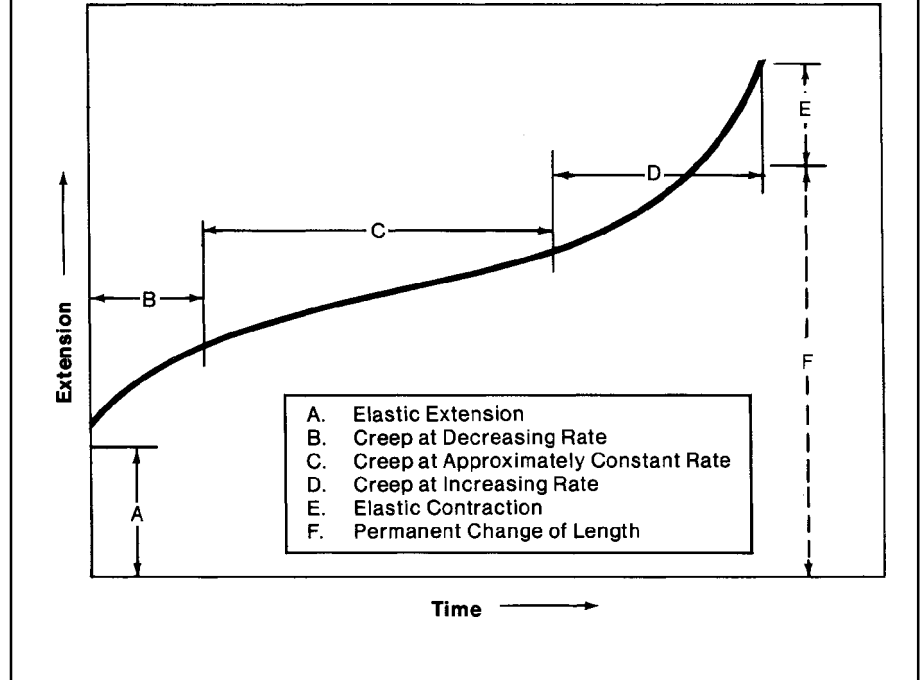
Figure 2
Effect of Cold Work on the Short-Time Tensile Properties of Type 301 at Elevated Temperature (1)

Figure 3 Short-Time Tensile Strengths (1)

ksi
MPa

Short-Time 0.2%-Offset Yield Strength

Austenitic Grades		Martensitic and Ferritic Grades	
Type		Type	
▣	202	▽	410
○	302	▼	430
●	309	⊕	446
△	310		
▲	316		
✕	321		
◻	347		

Short-Time Tensile Strength

Austenitic Grades		Martensitic and Ferritic Grades	
Type		Type	
▣	202	▽	410
○	302	▼	430
●	309	⊕	446
△	310		
▲	316		
✕	321		
◻	347		

Temperature

Typical short-time tensile strengths of various standard stainless steels at elevated temperature. All steels were tested in the annealed condition except for the martensitic Type 410, which was heat treated by oil quenching from 1800°F (982°C) and tempering at 1200°F (649°C).

7

Creep-Rupture

The creep rupture test (sometimes called the stress-rupture test) is identical to the creep test, except generally the stresses, and consequently the creep rates, are higher, and the test is carried to failure of the material. Rupture values are usually reported as the stress for rupture in 100, 1,000, 10,000 and 100,000 hours. The 100,000-hour rupture strength is one of the basic properties used in the establishment of design stresses. It should be noted that creep and creep-rupture tests are seldom carried out to the times corresponding to the intended service life. The stress, therefore, for a minimum creep rate of 1% in 100,000 hours is generally based on extrapolation of shorter-time tests to long time.

The stresses that will cause rupture in 10,000 and 100,000 hours of several austenitic stainless steels are shown in Figures 5 and 6 as a function of temperature. Stresses that will cause creep rates of 0.0001% and 0.00001% per hour are shown in Figures 7 and 8. Interpolation to other rupture times, creep rates, and stresses can be made by using Figures 9 to 17, which show the effects of applied stresses on the rupture times and creep rates for eight stainless steels at various temperatures.
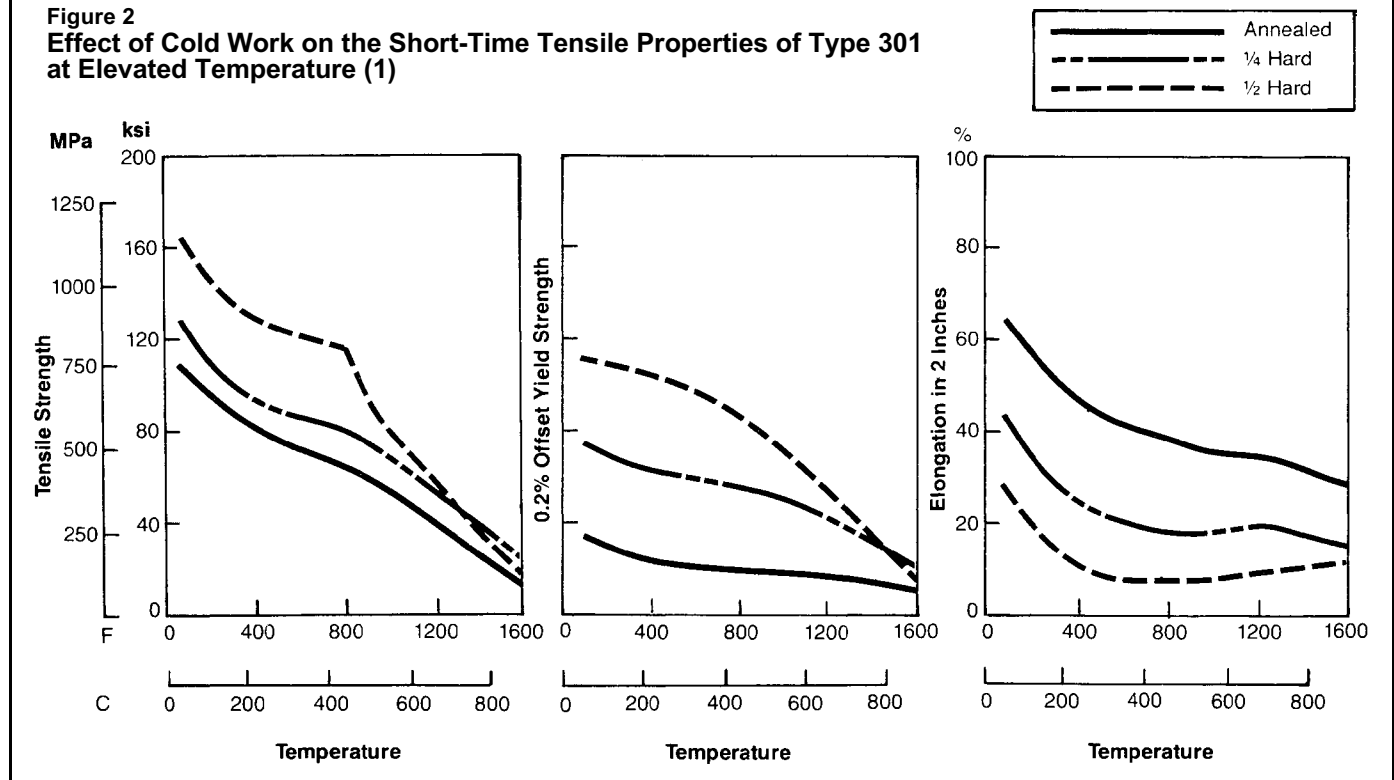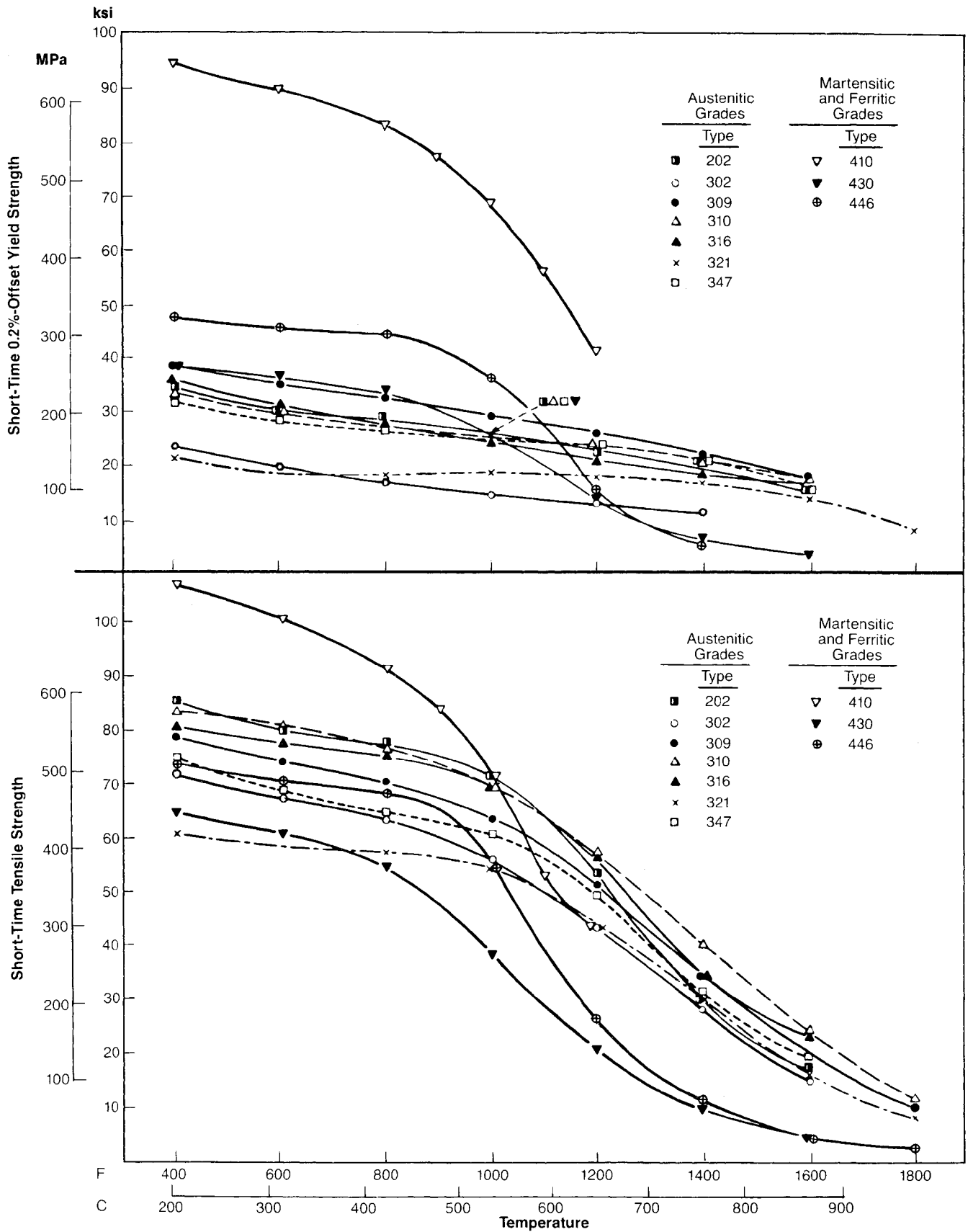
Much of the data available on the creep and rupture characteristics of stainless steels were published in ASTM Special Technical Publication No. 124, "The Elevated Temperature Properties of Stainless Steels", and in a supplement, ASTM Data Series Publication DS5-S1. ASTM Data Series DS5-S2, a supplement to the above-mentioned publications, offers an evaluation of elevated-temperature strength data for Types 304, 304L, 316, 316L, 321, and 347. DS5-S2 seeks to offer the best current assessments of the various properties that commonly form the basis for the setting of allowable stresses, and the assessments are presented in a form

Figure 5
Stress-Rupture Curves for Several Annealed Stainless Steels (2)

Figure 6
Stress-Rupture Curves for Several Annealed Stainless Steels (Extrapolated Data) (2)

8
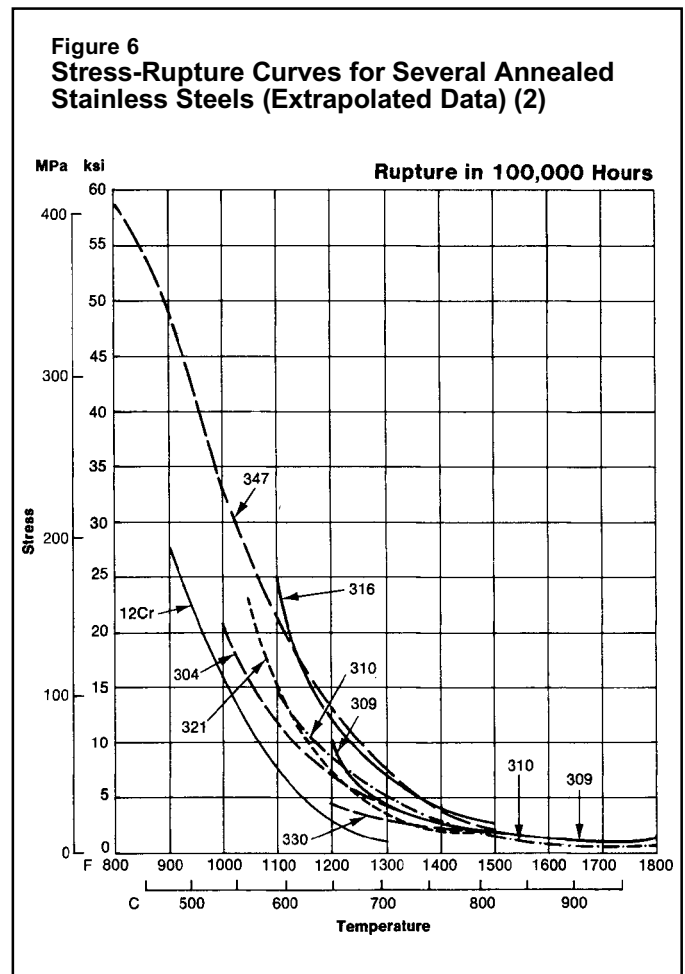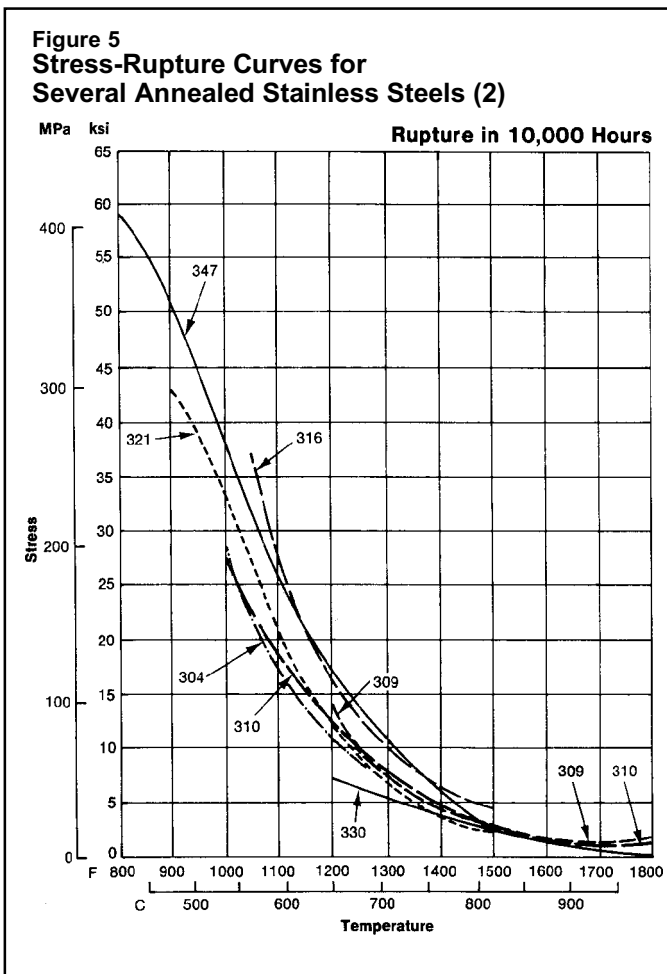
readily usable by specification groups for such a purpose. In the plots contained in DS5-S2, an attempt is made to distinguish between bar, plate, pipe and tubing. Also, a distinction is made among the regular stainless steel grades, the L grades, and the H grades.

The L grades of stainless steels, such as 304L and 316L, are those with a limited carbon content (0.03% max.). The H grades, however, prescribe wider carbon ranges (304H and 316H) or certain heat treatments (321H and 347H) ostensibly optimal for material intended for high-temperature service.

Where strength requirements are vital, as in pressure vessels, most elevated-temperature equipment is designed in accordance with the "Boiler and Pressure Vessel Code" of ASME. This code, originally issued strictly as a safety code, has kept pace with advances in technology. Today, it is said to represent an excellent compendium on minimum requirements for design, fabrication, inspection, and construction of safe equipment capable of a long period of usefulness. Separate codes are issued for various types of equipment, such as *unfired pressure vessels, power boilers,* and *nuclear vessels.*

Since specified design stresses are subject to change, designers should

Figure 7
Creep-Rate Curves for
Several Annealed Stainless Steels (2)

Figure 8
Creep-Rate Curves for
Several Annealed Stainless Steels (2)

Figure 9
Stress Versus Rupture-Time and
Creep-Rate Curves for Annealed Type 309
Stainless Steel Based on Average Data (2)

Figure 10
Stress Versus Rupture-Time and
Creep-Rate Curves for Annealed Type 309
Stainless Steel Based on Average Data (2)

9
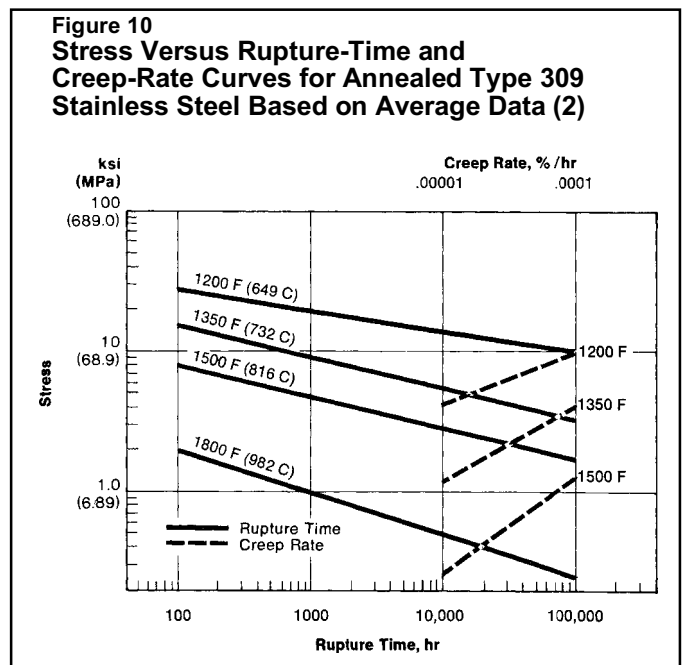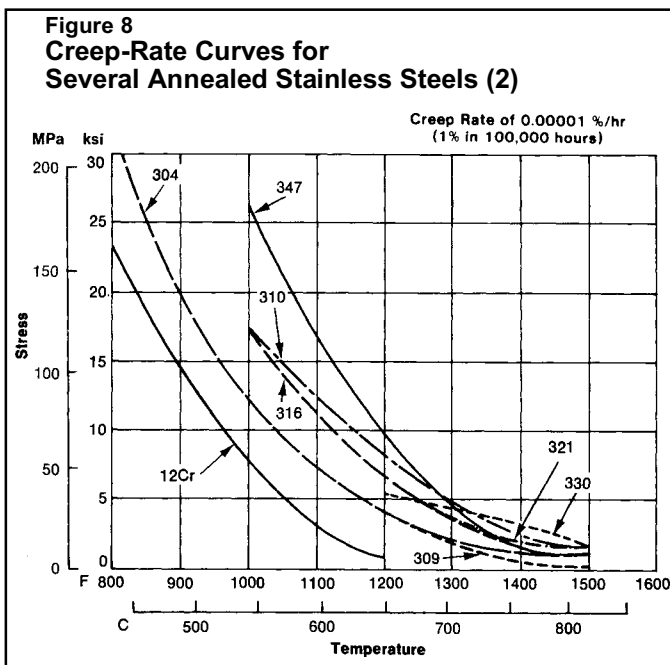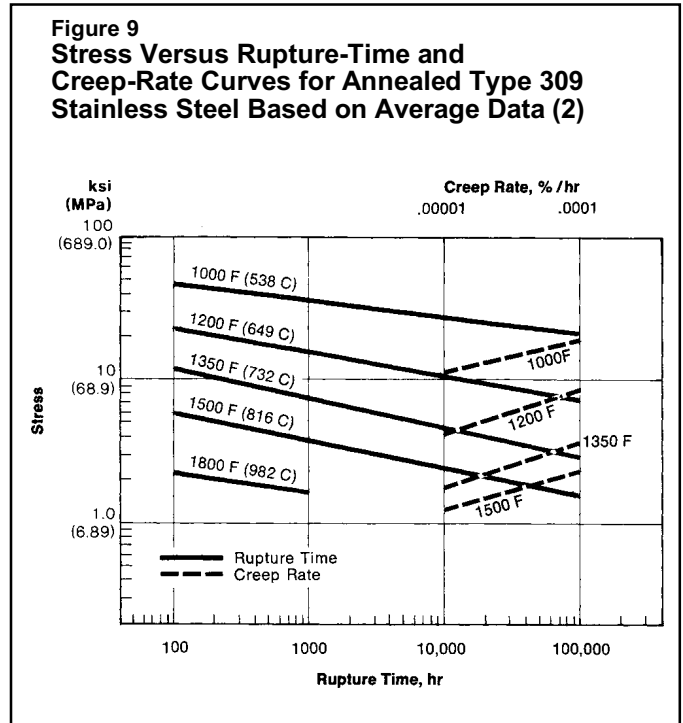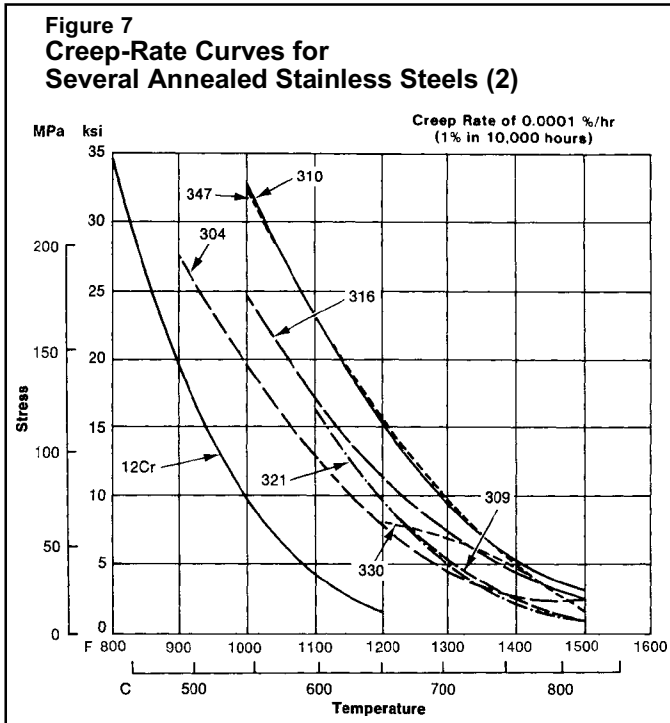
Figure 18 shows the allowable design stresses from the ASME Unfired Pressure Vessel Code, Section VIII Division I versus temperature for several austenitic and ferritic stainless steels, chromium-molybdenum steels, and carbon steel. This graph portrays the value of chromium additions to steel for elevated-temperature applications and the added advantage of nickel plus chromium. The maximum allowable stresses as specified in the ASME Code are derived from data employing suitable safety factors.

Figure 11
Stress Versus Rupture-Time and Creep-Rate Curves for Annealed Type 310 Stainless Steel Based on Average Data (2)

Figure 12
Stress Versus Rupture-Time and Creep-Rate Curves for Annealed Type 316 Stainless Steel Based on Average Data (2)

Figure 13
Stress Versus Rupture-Time and Creep-Rate Curves for Annealed Type 321 Stainless Steel Based on Average Data (2)

Figure 14
Stress Versus Rupture-Time and Creep-Rate Curves for Annealed Type 330 Stainless Steel Based on Average Data (2)

Figure 15
Stress Versus Rupture-Time and Creep-Rate Curves for Annealed Type 347 Stainless Steel Based on Average Data (2)

ksi (MPa)
100 (689.0)
10 (68.9)
1.0 (6.89)

Creep Rate, % /hr
.00001   .0001

800 F (426 C)
1000 F (538 C)
1200 F (649 C)
1350 F (732 C)
1500 F (816 C)

1000 F
1200 F
1350 F
1500 F

Stress

—— Rupture Time
- - - Creep Rate

Rupture Time, hr
100   1000   10,000   100,000
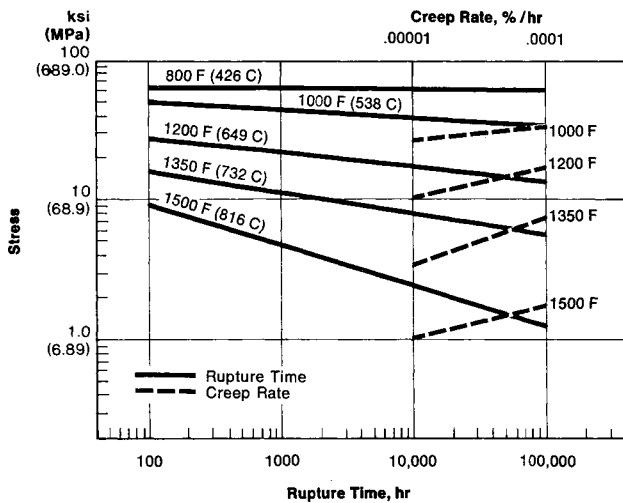
Figure 16
Stress Versus Rupture-Time and Creep-Rate Curves for Type 410 Stainless Steel Based on Average Data (3)

ksi (MPa)
100 (689.0)
10 (68.9)
1.0 (6.89)

Creep Rate, % /hr
.00001   .0001

900 F (482 C)
1000 F (538 C)
1100 F (593 C)
1200 F (649 C)

900 F
1000 F
1100 F
1200 F

Stress

—— Rupture Time
- - - Creep Rate

Rupture Time, hr
100   1000   10,000   100,000
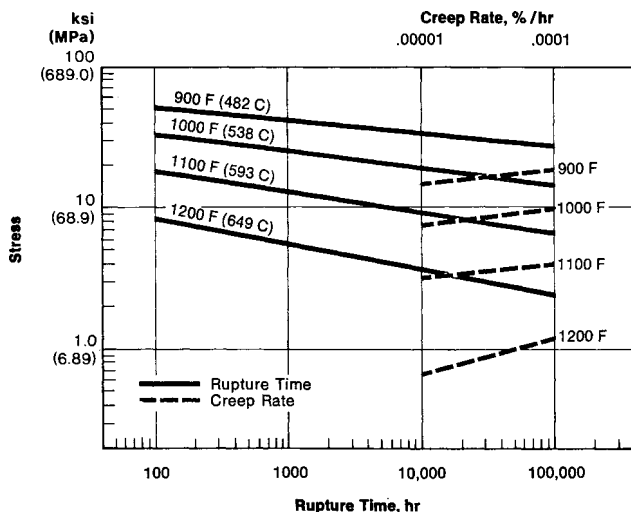
Figure 17
Stress Versus Rupture-Time and Creep-Rate Curves for 17 Cr and 18 Cr Stainless Steel Based on limited Data (3)

ksi (MPa)
100 (689.0)
10 (68.9)
1.0 (6.89)

Creep Rate, % /hr
.00001   .0001

17 Cr Steel
900 F (482 C)
1000 F (538 C)
1200 F (649 C)

18 Cr Steel
900 F
1000 F
1200 F

Stress

—— Rupture Time
- - - Creep Rate

Rupture Time, hr
1000   10,000   100,000
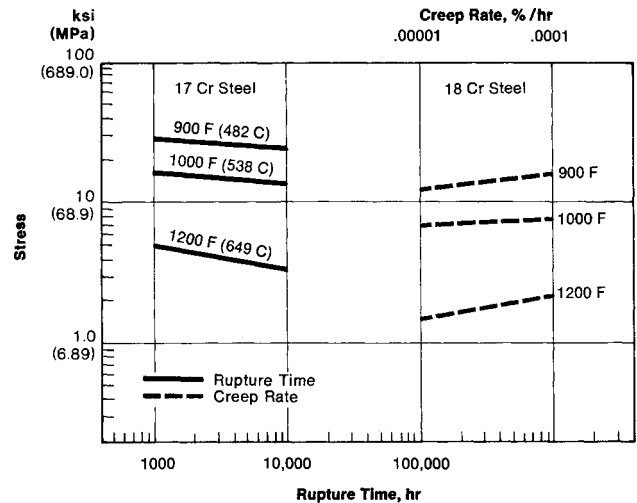
Figure 18
ASME Boiler & Pressure Vessel Code Allowable Stresses (4)

Section VIII 1974 Division 1

ksi
20
16
12
8
4

MPa
125
100
75
50
25

Maximum Allowable Stress in Tension

SA-213 Seamless Tube 2¼Cr—1Mo
SA-213 Seamless Tube 9Cr—1Mo
SA-268 Seamless Tube 17Cr—(430)
SA-213 Seamless Tube 18Cr—8Ni (304)
SA-210 Grade 1 Seamless Tube Carbon Steel

F   0   400   800   1200   1600   2000
C   0   200   400   600   800   1000
Metal Temperature

11

Table 1
Effect of Prolonged Holding at 900-1200°F (482-649°C)
on Room Temperature and Hardness (1)

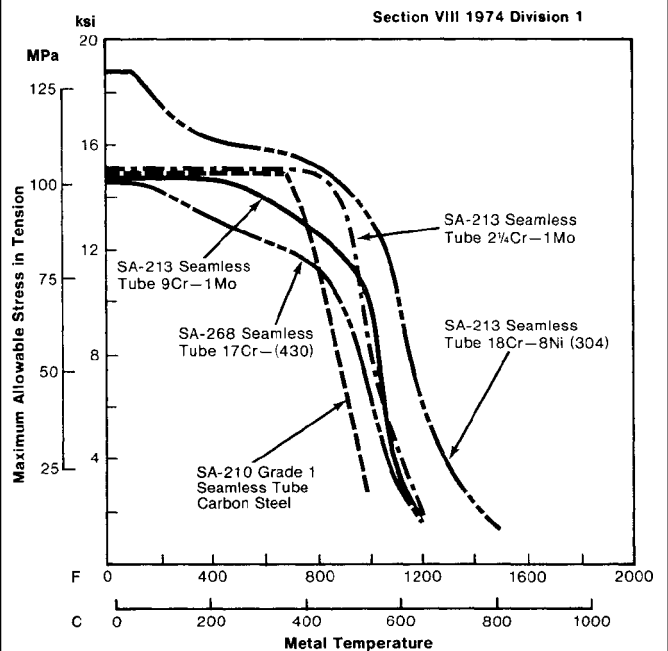| Stainless Steel Type	Room-Temperature Charpy Keyhole Impact Strength													Room-Temperature Brinell Hardness						
	Unexposed		after 1000 hr at						after 10,000 hr at						Unexposed	after 1000 hr at			after 10,000 hr at		
			900(482)		1050 (566)		1200°F (649°C)		900 (428)		1050 (566)		1200°F (649°C)			900 (482)	1050 (566)	1200°F (649°C)	900 (482)	1050 (566)	1200°F (649°C)
	ft-lb	J	ft-lb	J	ft-lb	J	ft-lb	J	ft-lb	J	ft-lb	J	ft-lb	J							
304	91	123	87	118	75	102	60	81	79	107	62	84	47	64	141	145	142	143	143	132	143
304L	82	111	93	126	76	103	72	98	85	115	71	96	63	85	137	140	134	134	143	143	143
309	95	129	120	163	85	115	43	58	120	163	51	69	44	60	109	114	109	130	140	153	159
310	75	102	–	–	48	65	29	39	62	84	29	39	2	3	124	119	119	130	152	174	269
316	80	108	86	117	72	98	44	60	87	118	49	66	21	28	143	151	148	170	145	163	177
321	107	145	101	137	90	122	69	94	88	119	72	98	62	84	168	143	149	166	156	151	148
347	56	76	60	81	55	75	49	66	63	85	51	69	32	43	169	156	167	169	156	169	123
405	35	47	–	–	36	49	26	35	–	–	39	53	34	46	165	–	143	137	–	143	143
410	33	45	–	–	41	56	27	37	39	53	3	4	21	28	143	–	114	154	124	143	128
430	46	62	–	–	32	43	34	46	1	1	3	4	4	5	184	–	186	182	277	178	156
446	1	1	–	–	1	1	1	1	1	1	1	1	1	1	201	–	211	199	369	255	239

Thermal Stability

With time at temperature, changes in metallurgical structure can be expected for almost any steel or alloy. In stainless steels, the changes can be softening, carbide precipitation, or embrittlement. Softening occurs in the martensitic stainless steels when exposed to temperatures approaching the original tempering temperature. Type 440C, for example, can be held at 900°F (482°C) for only short periods if the high hardness is to be retained, as graphically represented in Figure 19. Cold-worked austenitic stainless steels, as shown previously in Figure 2, may also soften at elevated temperature.

Carbide precipitation may occur in certain austenitic stainless steels in a temperature range of 800-1650°F (427-899°C). This causes a loss of toughness and – except for the low-carbon L grades and the stabilized types – may make the steel subject to intergranular corrosion in certain environments.

Embrittlement usually means the loss of room-temperature toughness. Embrittled equipment must be handled carefully to avoid impact when it is cooled down for maintenance. Table 1 shows how prolonged holding at temperatures of 900 to 1200°F (482 to 649°C) can affect room-temperature toughness of various stainless steels, while Figure 20 puts embrittlement into a better perspective with respect to the three "general-purpose" stainless steels (namely Types

Figure 19
Softening of Type 440C on Extended Holding at 900°F (482°C) (1)
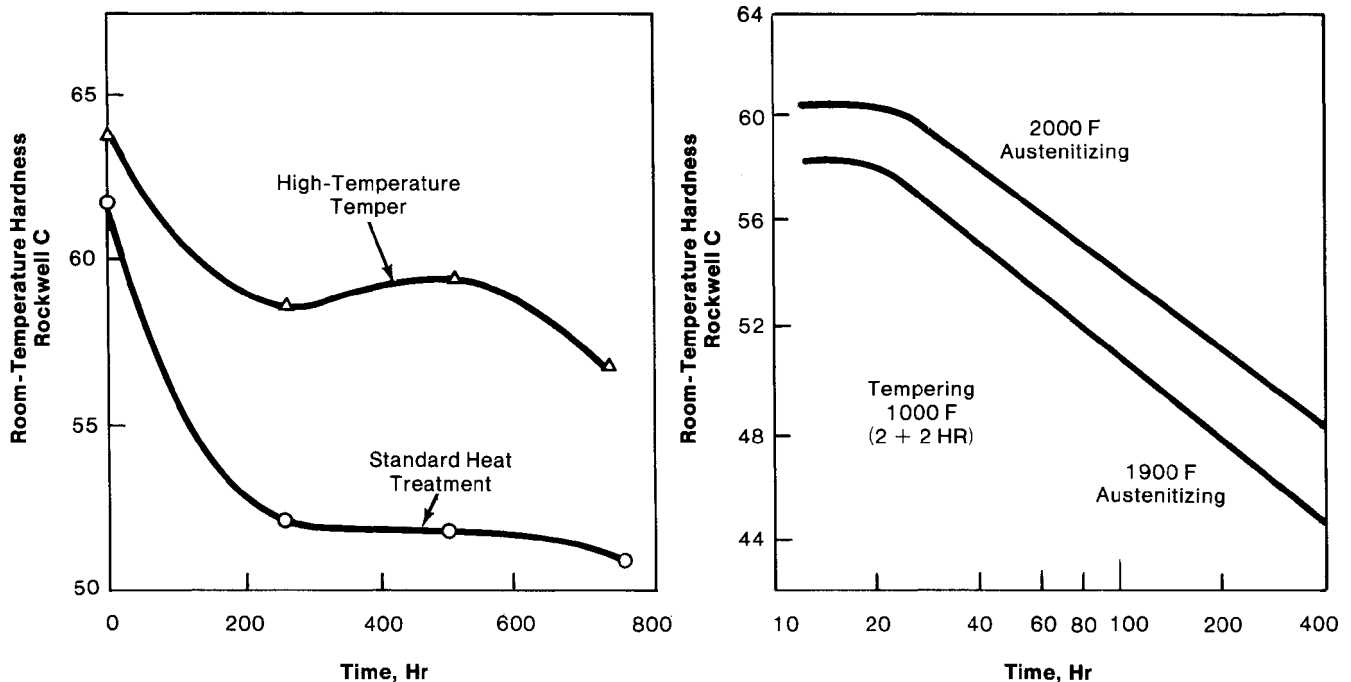
304, 410, and 430). Note that the transition temperature for Types 410 and 430 is near room temperature, while there is only a minor loss of toughness in Type 304. At these temperatures, embrittlement is rarely of concern with austenitic stainless steels.

Ferritic stainless steels are subject to another embrittlement phenomenon when exposed to temperatures of 700-950°F (371-510°C) over an extended period of time. Martensitic stainless steels with 12% chromium (such as Type 410) occasionally have also been known to display brittle tendencies after extended periods in the 700-950°F (371-510°C) temperature range. This phenomenon is called 885°F embrittlement because that is the temperature at which embrittlement is most pronounced.

Figure 21a shows the embrittling range peaking at 885°F for three time periods; 400, 1000, and 5000 hours, and Figure 21b shows that hardening tendency increases with time and chromium content.

885°F embrittlement results in low ductility, poor impact strength, and increased hardness and tensile strength at room temperature, which can cause the alloy to fracture if not handled carefully. The attempt to straighten heat-treating baskets, for example, could lead to brittle failure. The alloy, however, retains its desirable mechanical properties at operating temperatures, 500°F (260°C) and higher. Embrittlement can be removed by heat treating at 1100°F (593°C) or above, followed by air cooling.

Ferritic stainless steels are also subject to sigma-phase embrittlement when exposed to temperatures of 1000-1600°F (538-871°C) over extended periods of time. This results in a loss of ductility at room temperature. Sigma-phase embrittlement can be removed by heat treatment at 1850°F (1010°C) followed by air cooling.

GRAIN SIZE – The effect of grain size upon the strength and ductility of the high-temperature steels, particularly the austenitic grades, is marked. At all test temperatures in the range of 1000 to 1500°F (538 to 816°C) fine-grained austenitic stainless steels possess greater ductility than do coarse-grained structures. With short testing times at the lower test temperatures, the finer grained structures possess higher strength, while with increasing test time and/or temperatures the coarser-grained structures excel in rupture strength.

Figure 20
Effect of Holding 10,000 Hr at 900, 1050 and 1200°F (482, 566, and 649°C) on the Impact Characteristics of Type 410, 430, and 304 (5)
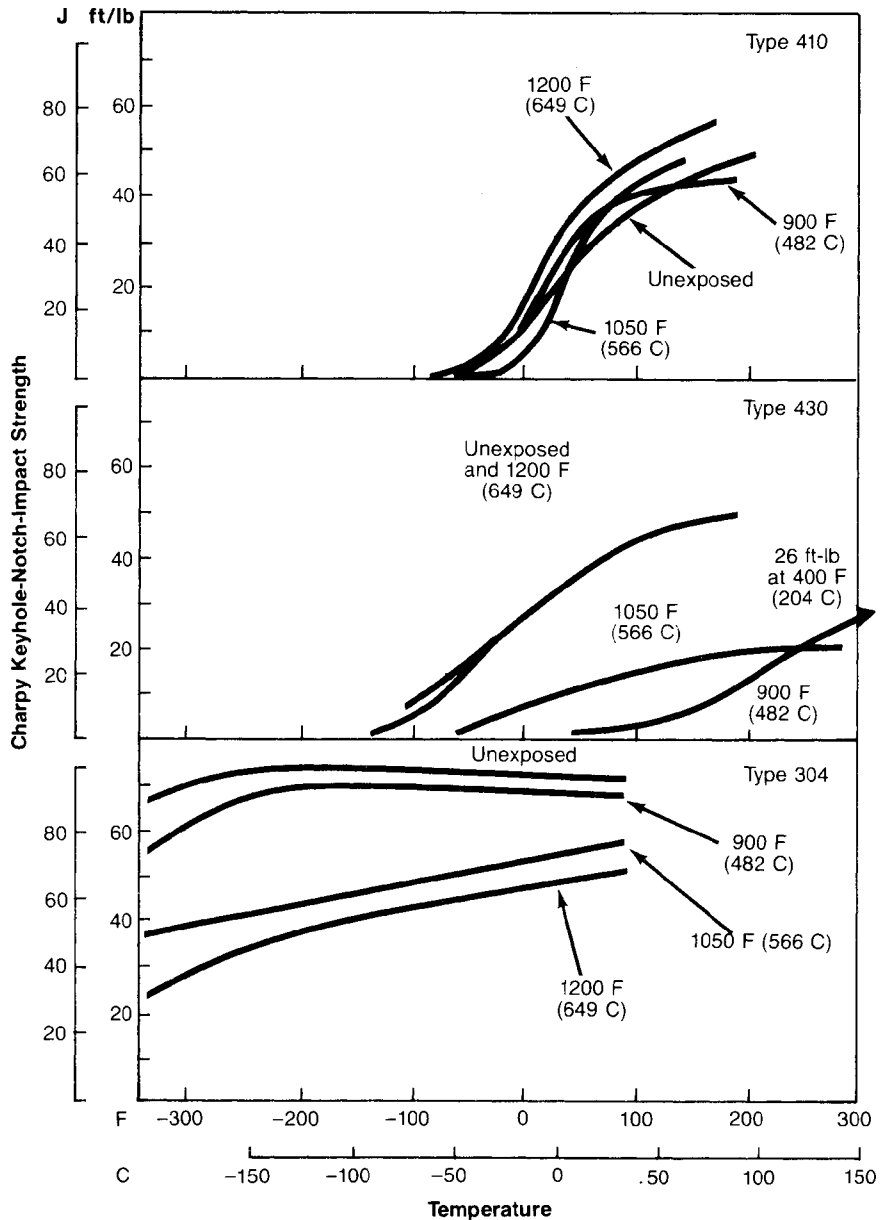
Hardness Values Were as Follows

| Type | Unexposed | DPN Hardness | | |
| | | After Exposure for 10,000 hr at | | |
		900°F (482°C)	1050°F (566°C)	1200°F (649°C)
410	125	125	124	123
430	185	274	198	169
304	138	140	147	141

Table 2
Sheet Specimen Short-Time Tensile Test Results (1)
Type 312 - Test Temperature 1400°F

Carbon %	Grain Size	Tensile Strength, psi	Elong. % in 2 in.
0.071	Fine	31,270	36.0
0.073	Coarse	34,130	15.0
0.12	Fine	43,400	36.0
0.12	Coarse	30,300	9.5

Figure 21
885°F Embrittlement (6)

Graph of Hardness Versus Aging Temperature for 400 Hours, 1000 Hours and 5000 Hours, Using 27% Chromium Steel – Type 446.

Graph of Hardness Versus Aging Time in Hours for Types 446, 430, 410 and 405 Chromium Steels. Hardening Tendency Increases with Chromium Con- tent. Aged at 885°F.

Table 2 shows that the strength relationship between fine- and coarse-grained structures may be reversed while the ductility of fine-grained material is superior.

For some applications a fine-grained material is desirable, while for others, a coarse-grained material will render longer service, depending on temperature and conditions of service. For example, substituting fine-grained Type 310 sheet, instead of the usual medium-to-coarse grained, greatly increases the service life of heat treating boxes or pans. Thermal stresses caused by rapid heating and cooling of containers made of the usual grain-sized Type 310 sheets were causing early failure by cracking. Substitution of fine-grained sheet afforded sufficiently higher ductility to permit relief of stresses by local elongation at points of stress concentration. This concept is graphically illustrated in Figure 22. When the quantity requirements permit special processing, alloys of the optimum grain size for the specific application can be supplied. It is best to consult with a stainless steel producer.

High-Temperature Stainless Steels

"H" GRADES – During the 1950s, utility boilers operating above 1000°F (538°C) at pressures above 1500 psi (10.3 MPa) were experiencing premature failures of Type 321 stainless steel. These failures were initially attributed to an extremely fine grain size occasioned by a low-temperature solution heat treatment. Reheat treatment at higher temperatures to produce a coarser grain structure reduced the incidence of failure.

Results of a subsequent research project provided evidence that the final solution heat treatment and not grain size was the most significant factor. Control of the carbon content was also found to be an important factor. Thus, a new designation was introduced, which incorporated specific heat treatments and control of carbon. It is significant that the H grades now have up to three times the service life without any indications of the premature creep failure experienced with the regular grades.

For Types 321 and 347, material meeting the "H" grade requirements, namely 321H and 347H, annealing is performed at a higher temperature depending upon whether the prior processing has involved hot or cold working. In contrast, Types 304H
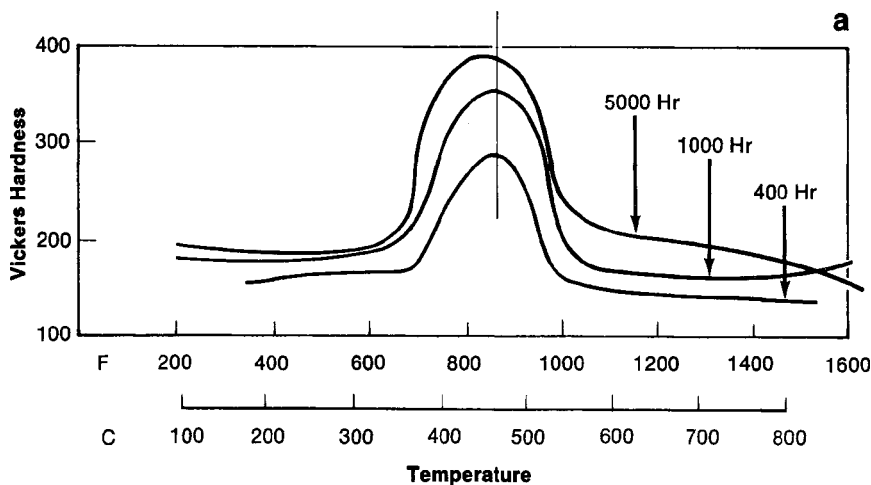
14
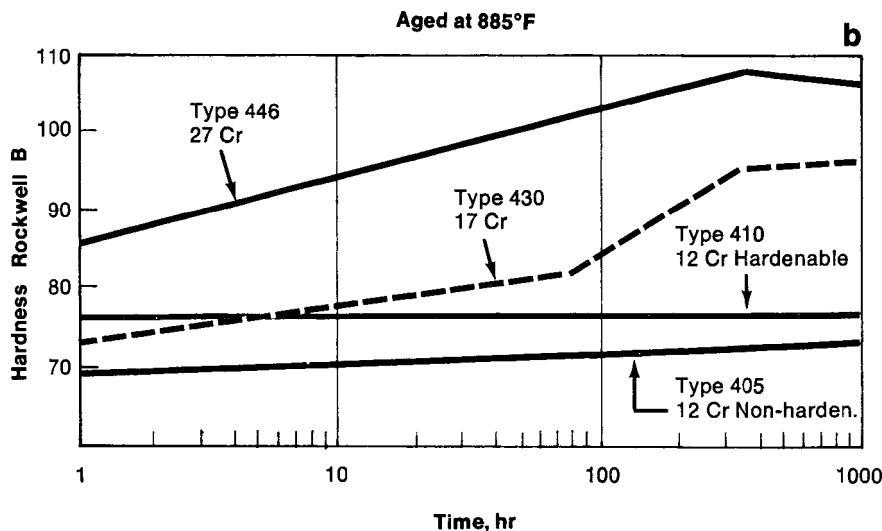
Figure 22
Effect of Grain Size on High-Temperature Strength and Ductility (1)

Numerals at plot points indicate average elongation at rupture for specimens of longest test.

and 316H are annealed at a lower temperature than for the regular grades, and independently of whether the material had been previously hot or cold worked. Moreover, in both 304H and 316H, the carbon contents are permitted to range between 0.04% and 0.10%, whereas the carbon content of the regular grade is limited to 0.08% maximum. Although there is no lower limit on carbon specifications for Types 304 and 316, the ASME Code stress tables impose, by means of a footnote, an effective minimum of 0.04% for service temperatures over 1000°F (538°C).
NITROGEN ADDITIONS – During the course of investigations on the "H" grades, it was found that nitrogen also played a role in improving the high-temperature strength of Type 304. In 1969, a symposium sponsored jointly by ASTM and ASME reviewed the effect of nitrogen on Types 304 and 316. The papers presented at this symposium are published in ASTM STP 522, "Elevated Temperature Properties as Influenced by Nitrogen Additions to Types 304 and 316 Austenitic Stainless Steels." Subsequent to this meeting, ASME approved the "N" grades of Types 304 and 316, which contain 0.10 to 0.16% nitrogen. Design stresses for these grades are presented in Table 3.

Table 3
ASME Design Stresses for Types 304N and 316N (7)

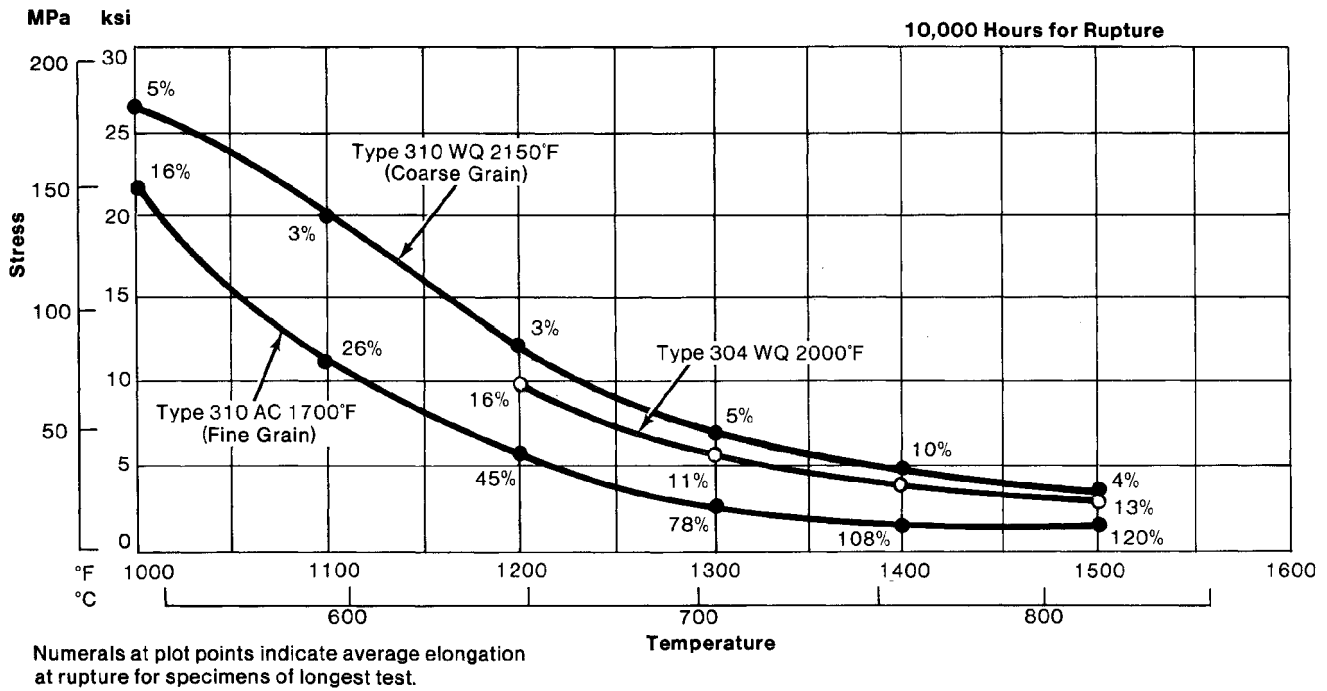| Temperature °F (°C)	Maximum Allowable Stress Section I, Section III Class 2 and 3, and Section VIII, Division 1 ksi[a]				Stress Intensity Section III, Class 1,and Section VIII, Division 2 ksi	
	Grade 304N		Grade 316N		Grade 304N	Grade 316N
75 (24)	20.0	20.0	20.0	20.0	23.33	23.33
100 (38)	20.0	20.0	20.0	20.0	23.33	23.33
200 (93)	17.9	20.0[b]	19.4	20.0[b]	23.33	23.33
300 (149)	15.7	19.0[b]	17.8	19.2[b]	22.6	23.33
400 (204)	14.1	18.3[b]	16.5	18.8[b]	20.4	22.33
500 (260)	13.0	17.8[b]	15.4	18.6[b]	18.7	22.2
600 (316)	12.4	17.4[b]	14.6	18.6[b]	17.8	21.1
650 (343)	12.2	17.3[b]	14.2	18.6[b]	17.55	20.5
700 (371)	11.9	17.15[b]	13.9	18.6[b]	17.2	20.1
750 (399)	11.75	16.9[b]	13.6	18.5[b]	16.9	19.6
800 (427)	11.55	16.6[b]	13.3	18.4[b]	16.65	19.2
850 (454)	11.3	16.3[b]	13.1	18.3[b]	…	…
900 (482)	11.05	15.9[b]	12.8	18.1[b]	…	…
950 (510)	10.8	15.6[b]	12.6	17.8[b]	…	…
1000 (538)	10.55	15.0[b]	12.4	17.4[b]	…	…
1050 (566)	10.3	12.4[b]	12.2	15.8[b]	…	…
1100 (593)	9.75	9.75	11.7	12.4[b]	…	…
1150 (621)	7.7	7.7	9.8	9.8	...	...
1200 (649)	6.05	6.05	7.4	7.4	…	…

[a]To convert ksi to MPa, multiply by 6.894757.

[b]Due to the relatively low yield strength of these materials, these higher stress values were established at temperatures where the short time tensile properties govern to permit the use of these alloys where slightly greater deformation is acceptable. The stress values in this range exceed 62½ percent, but do not exceed 90 percent of the yield strength at temperature. Use of these stresses may result in dimensional changes due to permanent strain.

*Approved by ASME Council March 9, 1972.

Figure 23
Linear Thermal Expansion of the Three Main Classes of Stainless Steel (1)

Figure 24
Thermal Conductivity of the Three Main Classes of Stainless Steel (1)
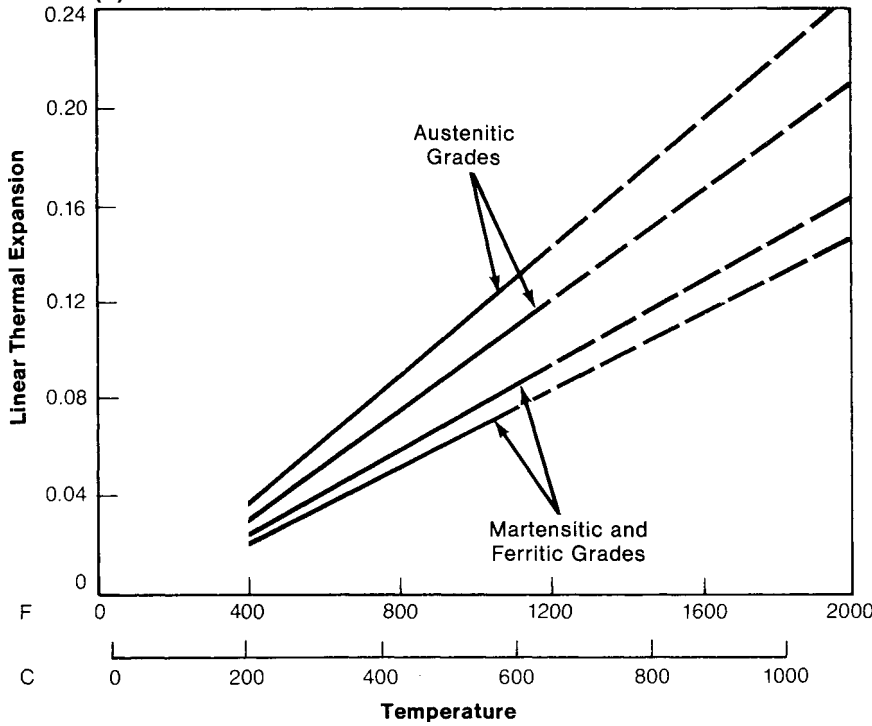
Physical Properties

Physical properties, such as linear expansion and thermal conductivity are of interest. Figure 23 shows 300 Series stainless steels to have greater thermal expansion than the 400 Series types, which should be considered in designing equipment for high-temperature service and when joining dissimilar types.

Thermal conductivity is also different among the three metallurgical categories of stainless steels as suggested by Figure 24. However, in heat exchange applications film resistance, fouling, and other surface factors have a far greater effect on heat transfer than the alloy itself.

Stainless steels are used extensively for heat exchangers because their ability to remain clean enhances heat transfer efficiency. For example, Figure 25 illustrates that films and scale on exchanger surfaces impair heat transfer to a far greater extent than the metal wall, which accounts for only 2% of the total resistance to heat flow. Table 4 supports this by showing a comparison of "U" values among four different metals – namely copper, aluminum, stainless steel, and carbon steel – in identical operating environments.

The fluctuating thermal stresses resulting from periodic changes in temperature can lead to thermal fatigue. As a result of their low thermal conductivity and high thermal expansion,

Figure 25
Factors Affecting Heat Transfer (8)

Steam Side Water Film	18%
Steam Side Fouling	8%
Tube Wall	2%
Water Side Fouling	33%
Water Side Film	39%

Table 4
Effect of Metal Conductivity on "U" Values (9)

Application	Material	Film Coefficients Btu/hr/ft^2/°F (W/m^2 • K)		Thermal Conductivity of Metal Btu/hr/ft^2/°F/in. (W/m • K)	"U" Value Btu/hr/ft^2/°F (W/m^2 • K)
		h_o	h_i		
Heating water with saturated steam	Copper	300 (1704)	1000 (5678)	2680 (387)	229 (1300)
	Aluminum	300 (1704)	1000 (5678)	1570 (226)	228 (1295)
	Carbon Steel	300 (1704)	1000 (5678)	460 (66)	223 (1266)
	Stainless Steel	300 (1704)	1000 (5678)	105 (15)	198 (1124)
Heating air with saturated steam	Copper	5 (28)	1000 (5678)	2680 (387)	4.98 (28)
	Aluminum	5 (28)	1000 (5678)	570 (226)	4.97 (28)
	Carbon Steel	5 (28)	1000 (5678)	460 (66)	4.97 (28)
	Stainless Steel	5 (28)	1000 (5678)	105 (15)	4.96 (28)

where h_o=outside fluid film heat-transfer coefficient
h_i =inside fluid film heat-transfer coefficient
Stainless steel is 300 Series Type

$$"U" \ = \ \cfrac{1}{\cfrac{1}{h_o} + \cfrac{\text{thickness of metal wall}}{\text{thermal conductivity}} + \cfrac{1}{h_i}}$$

the 300 Series stainless steels are more sensitive to thermal fatigue than the 400 Series types. Accordingly, complicated fabricated structures subject to alternate heating and cooling require design techniques incorporating the following; minimization of temperature differentials, use of expansion joints and other means of permitting movement without distortion, and avoidance of notches and abrupt change of section.

MODULUS OF ELASTICITY – The tensile modulus of elasticity of the ferritic steels (alloy and stainless) is close to 30,000,000 psi (206.8 GPa) at room temperature. It decreases linearly to about 25,000,000 psi (172.4 GPa) at 900°F (482°C), and then it begins to drop rapidly at higher temperatures, as illustrated in Figure 26. The modulus of elasticity for the austenitic stainless steels is about 28,000,000 psi (193 GPa) at room temperature, and there is a linear decrease to about 20,000,000 psi (137.9 GPa) at 1300°F (704°C) before a rapid drop begins. This is illustrated in Figure 27.

Caution should be used in employing elastic moduli for design at elevated temperatures where creep (plastic deformation) may occur.

Figure 26
Tensile Modulus for Ferritic Steels (Alloy and Stainless) (10)

Figure 27
Tensile Modulus for Austenitic Stainless Steels (10)
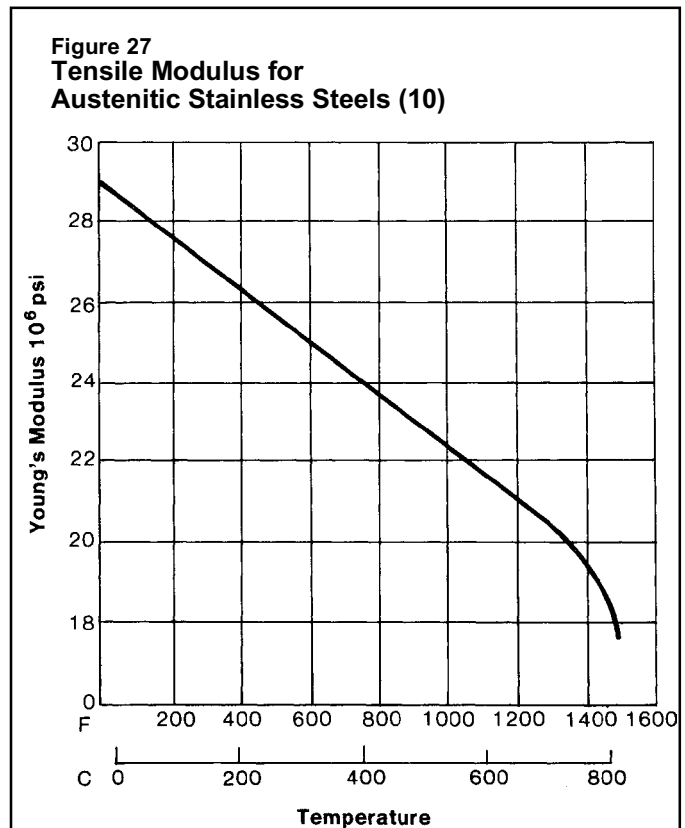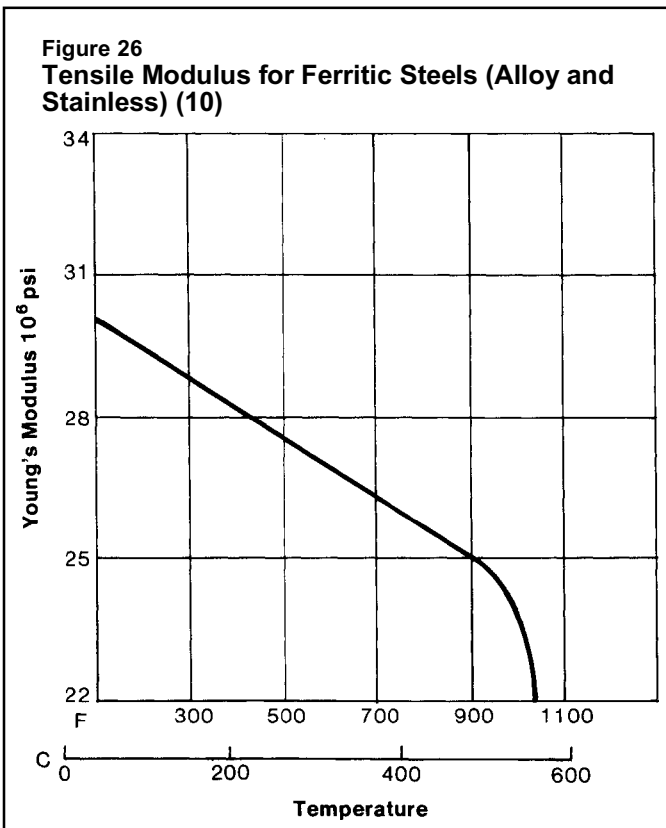
Figure 28
Effect of Chromium Content on Corrosion Rate (1) (In Normal Atmosphere)
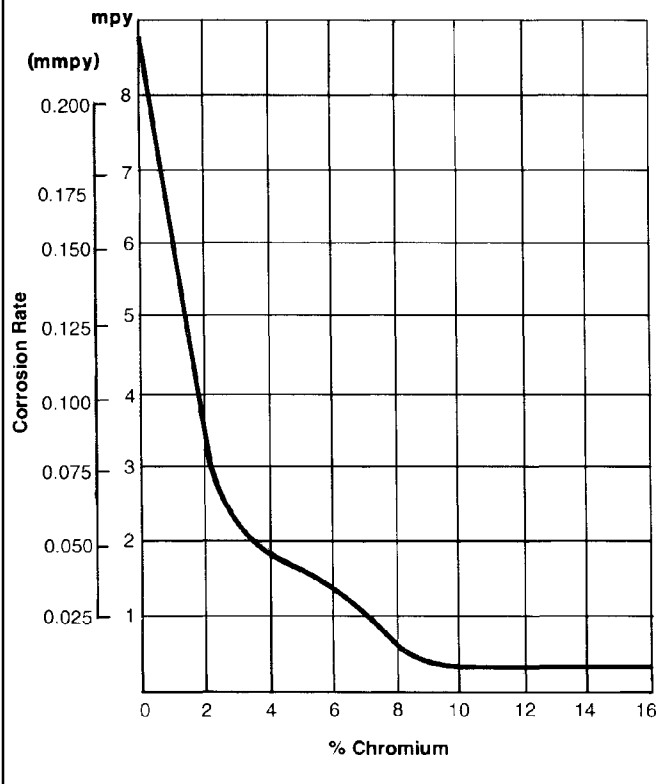
Figure 29
Effect of Chromium Content on Scaling Resistance (At 1800°F or 982°C) (1)
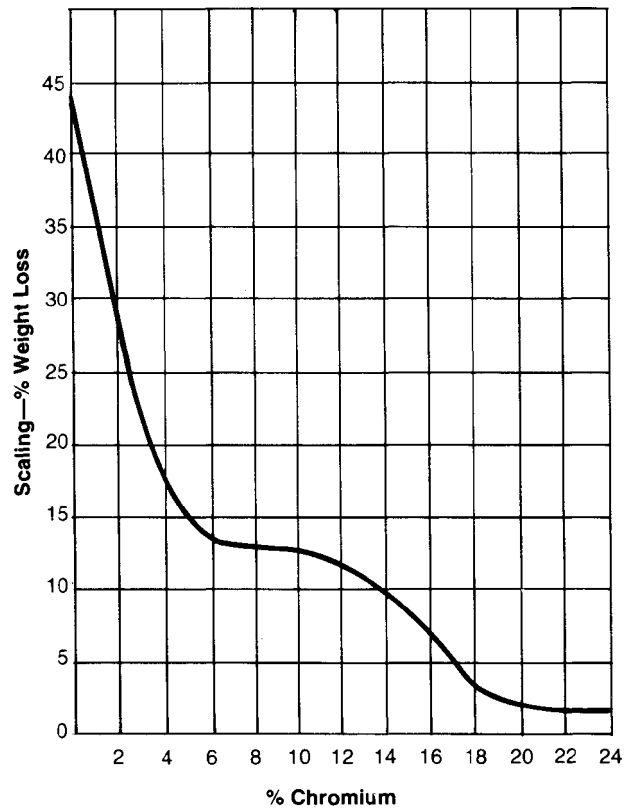
CORROSION RESISTANCE AT ELEVATED TEMPERATURES

Chromium is the principal alloying element that imparts to stainless steels their corrosion-resistance qualities by combining with oxygen to form a thin, transparent chromium-oxide protective film on the surface. This concept is broadly illustrated by Figure 28. When stainless steels are exposed at elevated temperatures, changes can occur in the nature of the surface film. For example, at mildly elevated temperatures in an oxidizing gas, the film can remain protective because diffusion of oxygen through the film is extremely slow (within practical temperature limits). As would be expected, the oxidation resistance is in proportion to chromium content, as suggested by Figure 29, which shows how the scaling resistance of chromium-iron alloys at a given temperature improves with increasing chromium content. However, under extreme conditions of high temperature *plus corrosion*, the surface film may not be protective at all.

Because of the many possible variables involved – temperature, corrosive environment, alloy composition, time, operating practice (constant service temperature versus intermittent service), etc.– it is impractical to discuss in detail every combination. Therefore, the following data should serve only as a starting point for material selection and not as a substitute for service tests.

Oxidation

In nonfluctuating-temperature service, the oxidation resistance (or scaling resistance) of stainless steels depends on chromium content. Stainless steels with less than 18% chromium (ferritic grades primarily) are limited to temperatures below 1500°F (816°C). Those containing 18 to 20% chromium are useful to temperatures of 1800°F (982°C), while adequate resistance to scaling at temperatures up to 2000°F (1093°C) requires a chromium content of at least 25%, such as Types 309, 310, or 446. Figure 30 provides an indication of the relative scaling resistance of commonly used high-temperature alloy steels.

In many processes, isothermal (constant temperature) conditions are not maintained and process temperatures vary. Expansion differences between the base metal and the protective film (or scale) during heating and cooling can cause cracking and spalling of the protective scale. This allows the oxidizing media to attack the exposed metal surface.

The spalling resistance of stainless steels is greatly improved with higher nickel levels, as suggested by Figure 31. Nickel reduces the thermal expansion differential between the base metal and the oxide film and thereby reducing stresses at the base metal-oxide interface during cooling. Also, Type 446 and the new proprietary ferritic chromium-molybdenum stainless steels have a relatively low coefficient of thermal expansion, which tends to enhance spalling resistance. Additions of silicon also increase resistance to oxidation, such as Type 314, but silicon tends to decrease high-temperature strength.

The maximum service temperature based on a rate of oxidation of 10mg. per sq. cm. in 1000 hours is given for several stainless steels in Table 5 for both constant and intermittent service.

EFFECT OF ATMOSPHERE – Much attention is given to the compatibility of stainless steels with air or oxygen. However, trends in the design of steam and other forms of power generation have resulted in a growing interest in oxidation in such environments as carbon monoxide, carbon dioxide, and water vapor. Exposure to mild conditions in these environments leads to the formation of the protective oxide film described earlier, but when conditions become too severe, film breakdown can occur. The onset of this transition is unpredictable and sensitive to alloy composition.

Although the reaction mechanisms are probably similar in air, oxygen, water vapor, and carbon dioxide, reaction rates may vary considerably. For example, similar scaling behavior has been observed in air and oxygen except that scale breakdown occurs more rapidly in oxygen. For this reason, results obtained in air should be applied with care when considering service in pure oxygen.

An increase in corrosion rates can be expected in the presence of water vapor,

Figure 30
Comparative Scaling Behavior of Various Steels During 1000-Hr Exposures in Air at Temperatures from 1100 to 1700°F (595 to 925°C) (11)
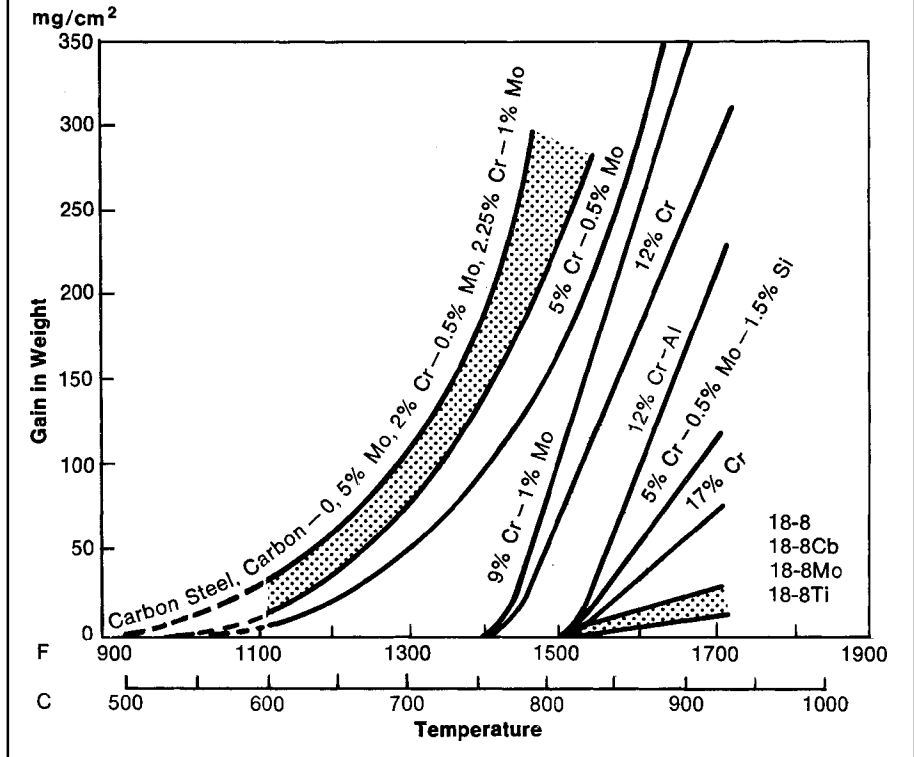
Figure 31
Effect of Nickel on Scaling Resistance (1)

Scaling resistance of some iron-chromium-nickel alloys in cycling-temperature conditions at 1800°F (982°C). Cycle consisted of 15 min. in the furnace and 5 min. in air. Sheet specimens 0.031 in. (0.787 mm) thick were exposed on both sides.
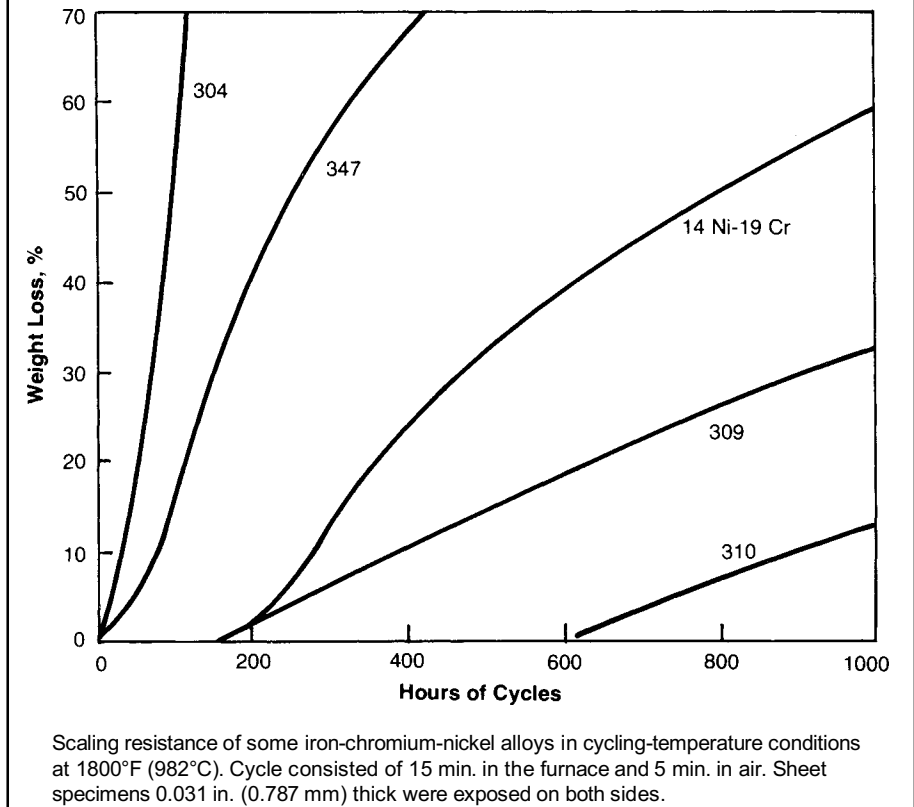
	Table 5 **Suggested Maximum Service Temperatures in Air (1)**			
	Intermittent Service		Continuous Service	
AISI Type	**°C**	**°F**	**°C**	**°F**
201	815	1500	845	1550
202	815	1500	845	1550
301	840	1550	900	1650
302	870	1600	925	1700
304	870	1600	925	1700
308	925	1700	980	1800
309	980	1800	1095	2000
310	1035	1900	1150	2100
316	870	1600	925	1700
317	870	1600	925	1700
321	870	1600	925	1700
330	1035	1900	1150	2100
347	870	1600	925	1700
410	815	1500	705	1300
416	760	1400	675	1250
420	735	1350	620	1150
440	815	1500	760	1400
405	815	1500	705	1300
430	870	1600	815	1500
442	1035	1900	980	1800
446	1175	2150	1095	2000

Figure 32
Oxidation of Types 302 and 330 in Wet and Dry Air (13)
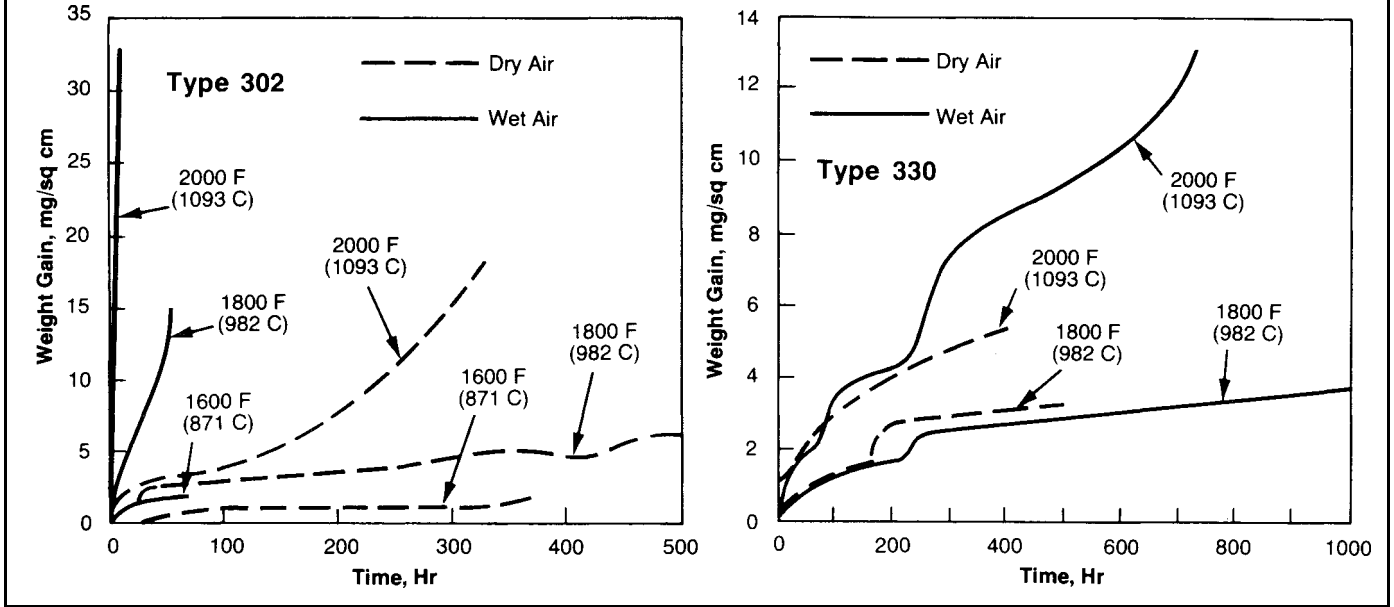
as suggested by Figure 32, which illustrates the effect of moist air on the oxidation of Types 302 and 330. Type 302 undergoes rapid corrosion in wet air at 2000°F (1093°C), whereas a protective film is formed in dry air. The higher-nickel Type 330 is less sensitive to the effects of moisture, so it is assumed that increased chromium and nickel permits higher operating temperatures in moist air. Types 309 and 310 are superior at temperatures greater than 1800°F (982°C),

and Type 446 is usable at temperatures approaching 2000°F (1093°C). The addition of moisture to oxygen significantly increases the corrosion rates of Types 304, 316, 321, and 347, so for these and the other grades listed in Table 5, the temperature limits should be adjusted downwards.

It is difficult to indicate maximum service temperatures for steam service, one reason being the sensitivity of corrosion rate to surface condition.

(Smooth, cold worked surfaces tend to reduce corrosion effects in steam service.) Most austenitic stainless steels can be used at temperatures up to 1600°F (871°C), and Types 309, 310, and 446 at higher temperatures. Types 304, 321, and 347 are being used in low-pressure steam systems at temperatures approaching 1400°F (760°C). Scale on Types 304, 316, and 347 tends to exfoliate at higher temperatures.

The oxidation of stainless steels in

Figure 33
Oxidation of Type 304 in Carbon Dioxide at 1 atm Pressure (13)
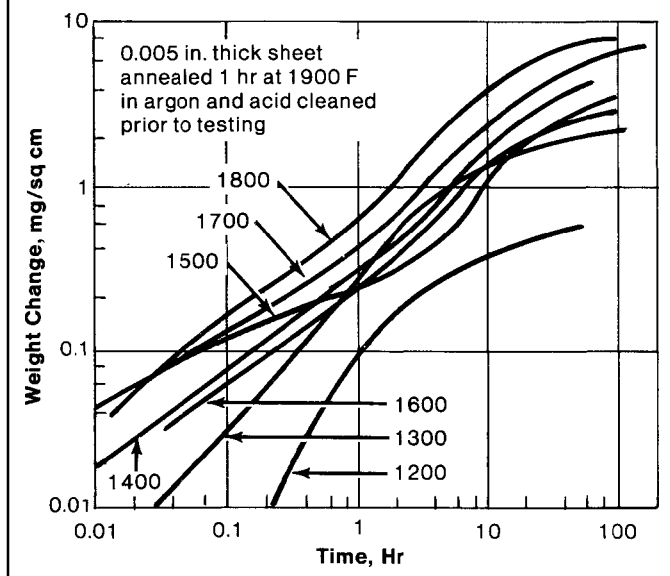
Figure 34
Average Corrosion Rates
High-Temperature Sulphur Corrosion
Hydrogen-Free Environment (14)
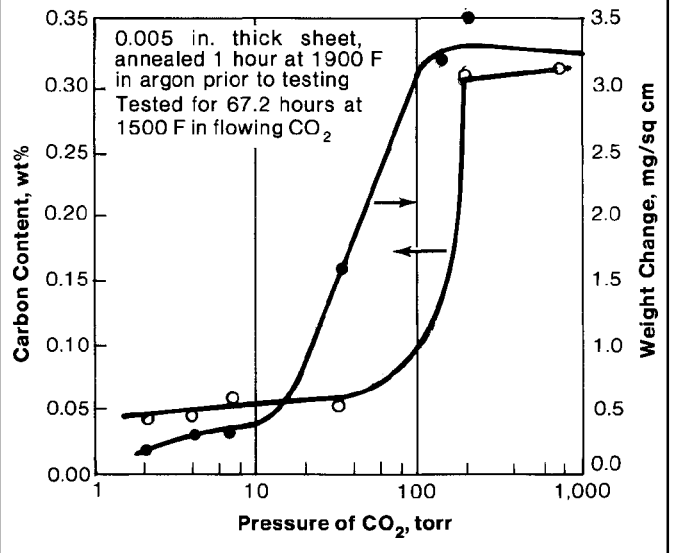
carbon dioxide and carbon dioxide/ carbon monoxide atmospheres at 1100-1800°F (593-982°C) is of interest because of their use in gas-cooled nuclear reactors. Detailed studies were conducted on the oxidation of Type 304 in carbon dioxide over a temperature range of 1200 to 1800°F (649-982°C), the results of which are illustrated in Figures 33 and 34. Figure 33 shows the oxidation of Type 304 in carbon dioxide at one atmosphere pressure, at different temperatures, while Figure 34 shows the effect of carbon dioxide pressure on the carburization and oxidation of Type 304 at 1500°F (816°C). A rapid increase in scaling rate occurs at about 10 torr, whereas rates are insensitive to pressure above 100 torr. The conclusion is that oxidation is greater in carbon dioxide than in air.

Type 406 is highly resistant to carbon dioxide at 1700°F (927°C), apparently due to its aluminum content. Also, it appears that higher nickel contents promote the resistance to oxidation in carbon dioxide environments. For carbon dioxide service, the scaling temperatures for Type 410, 430, 302, 321, 316, and 347, as listed in Table 5 should be revised downward about 100-200°F (38-93°C), whereas the higher -chromium-nickel Types 309, 310, and 330 might be used at temperatures close to those listed for service in air.

Sulfidation

Sulfur attack is second only to air oxidation in frequency of occurrence in many industries, and it is of even greater consequence because deterioration is likely to be more severe. Like oxidation, sulfidation proceeds by converting metal to scale, which may be protective except that metal sulfides melt at lower temperatures than comparable oxides, and they may fuse to metal surfaces. Also, sulfides are less likely to form tenacious, continous protective films. Fusion and lack of adherence can result in accelerated corrosion.

As with oxidation, resistance to sulfidation relates to chromium content. Unalloyed iron will be converted rather rapidly to iron sulfide scale, but when alloyed with chromium, sulfidation resistance is enhanced, as illustrated by Figure 35. Silicon also affords some protection against sulfidation.

The low melting point nickel/nickel sulfide eutectic, however, may be formed on the austenitic stainless steels containing more than 25% nickel even in the presence of high chromium. The

occurrence of molten phases during high-temperature service can lead to catastrophic destruction of the alloy.

In addition to the usual factors of time, temperature, and concentration, sulfidation depends upon the form in which the sulfur exists. Of particular interest is the effect of sulfur vapor, sulfur dioxide, hydrogen sulfide, and flue gases.

SULFUR VAPOR – Sulfur vapor readily attacks the austenitic grades. In tests, relatively high corrosion rates were encountered in flowing sulfur vapor at 1060°F (571°C), as suggested by Table 6.

Table 6 Corrosion of Stainless Steels in Sulfur Vapor at 1060°F (12)	
AISI Type	Corrosion Rate* (mpy)
314	16.9
310	18.9
309	22.3
304	27.0
302B	29.8
316	31.1
321	54.8

*Corrosion rate based on 1295 hr tests.

Figure 35
AVERAGE CORROSION RATES
High Temperature Sulfur Corrosion
Hydrogen Free Environment (14)

As compiled from 1961 A.P. I. questionaire. Data from industry (desulfurizing process) and published or reported data (nondesulfurizing process)
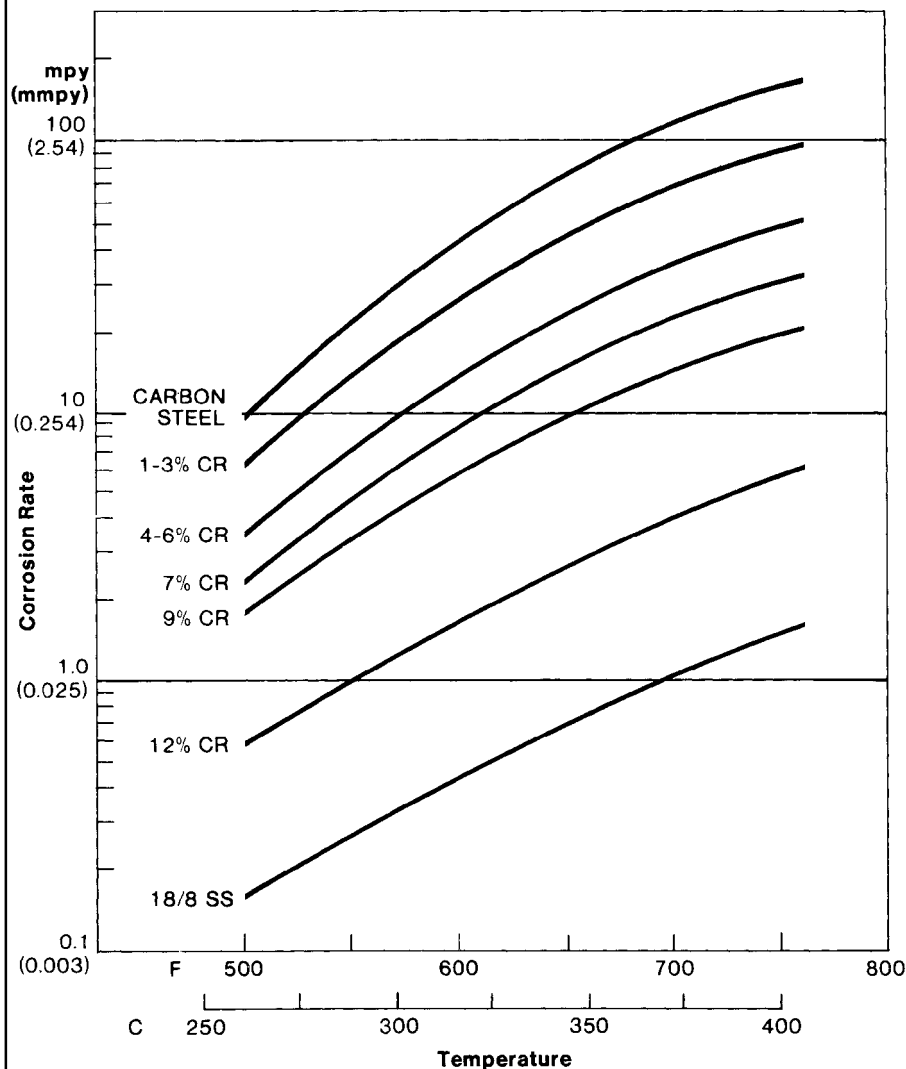
Figure 36
Sulfide Corrosion Reaction

$$Fe + H_2S \rightleftharpoons FeS + H_2$$

Steel
Fe

Fe IONS
Diffusing out

FeS
Ferrous Sulfide Scale

Hydrogen
— H_2

Reduces Scale
Minimizes Carbon
Deposition

Hydrogen Sulfide
— H_2S

Adsorption at
Corroding Surface

Table 7
Corrosion Rate of Stainless Streels in Flue Gases (19)
(Exposure 3 Months)

AISI Type	Corrosion Rate (mpy)		
	Coke Oven Gas (1500°F)	Coke Oven Gas (1800°F)	Natural Gas (1500°F)
430	91	236†	12
446 (26 Cr)	30	40	4
446 (28 Cr)	27	14	3
302B	104	225†	–
309S	37*	45	3
310S	38*	25	3
314	23*	94	3

*Pitted specimens-average pit depth.   †Specimens destroyed.

Figure 37
Corrosion Rate Curves for H₂/H₂S Environments (16)

mmpy   mpy

H2S Concentrations Above 1 Mole %

Carbon Steel 5% Cr

9% Cr

11-13% Cr

18% Cr—8% Ni

Corrosion Rate

Temperature

It has been reported, however, that Type 310 has been successfully used for a sulfur-vapor line at 900°F (482°C).

In liquid sulfur, most austenitic grades are resistant up to 400°F (240°C), with the stabilized Types 321 and 347 showing satisfactory service to 832°F.

SULFUR DIOXIDE – In a series of laboratory tests, Type 316 was exposed to mixtures of oxygen and sulfur dioxide, varying from 100% oxygen to 100% sulfur dioxide, at temperatures ranging from 1100 to 1600°F (593 to 871°C). Results indicate that the rate of attack was largely independent of the gas composition, and no scale developed – only a heavy tarnish.

HYDROGEN SULFIDE – The rate of corrosion in H2S depends on concentration, temperature, pressure and permeability of the sulfide scale. The presence of chromium in the steel helps to stabilize the scale and slow the diffusion process. However, at high pressure and temperature when hydrogen is present, the attack is more aggressive, to the extent that low-chromium steels are not adequate.

The system pressure increases the H₂S partial pressure, making it more reactive. Molecular hydrogen dissociates slightly to provide atomic hydrogen, which is

Figure 39
Effect of Chromium on the
Oxidation Resistance of Steel in a
Normal Combustion Atmosphere. (18)

Max. Metal Temp F for Oxidation Resistance

Chromium in Steel %
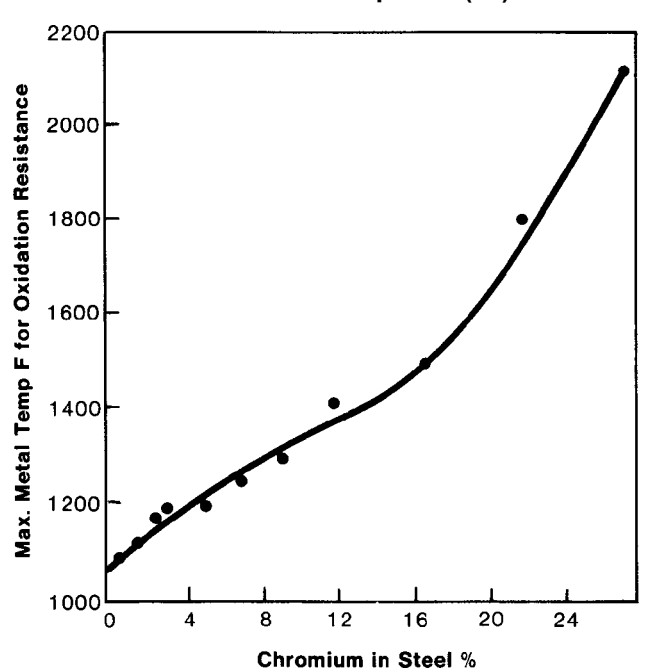
more reactive and can diffuse through steel. The hydrogen combines with the sulfide scale, reducing it and creating a porous structure through which the iron and sulfur ions can maintain high diffusion rates.

In the case of the iron-chromium alloys resistance to H_2S attack decreases up to 5-9% chromium. However, higher chromium content and the addition of nickel improve resistance, and it has been established that stainless steels with 18-20% chromium and 8-20% nickel are the most desirable for long-term service. Data from laboratory tests in which steels were evaluated in flowing H_2/H_2S gas confirms this. Figure 36 shows the concept of hydrogen penetration and Figure 37 shows corrosion rates for H_2S concentrations above one mole percent. Each curve represents the maximum rate of corrosion that would be expected under commercial operating conditions.

The isocorrosion curves shown in Figure 38 show the effected of hydrogen sulfide and temperature on the austenitic stainless steels.

FLUE GASES – It is extremely difficult to generalize corrosion rates in flue and process gases since gas composition and temperature may vary considerably within the same process unit. Combustion gases normally contain sulfur compounds; sulfur dioxide is present as an oxidizing gas along with carbon dioxide, nitrogen, carbon monoxide, and excess oxygen. Protective oxides are generally formed, and depending on exact conditions, the corrosion rate may be approximately the same as in air or slightly greater. The resistance of stainless steels to normal combustion gases is increased by successive increments in chromium content, as shown in Figure 39. Table 7 indicates the beneficial effect of chromium and the influence of fuel source.

Reducing flue gases contain varying. amounts of hydrogen sulfide, hydrogen, carbon monoxide, carbon dioxide and nitrogen. The corrosion rates encountered in these environments are sensitive to hydrogen sulfide content and temperature, and satisfactory material selection often necessitates service tests. Table 8 illustrates the effect of sulfur content on the corrosion of Types 309, 310 and 330 in oxidizing and reducing flue gases. The deleterious effect of high nickel content is apparent (Type 330).

Figure 38
Effect of Temperature and H_2S on Corrosion Rate (17)
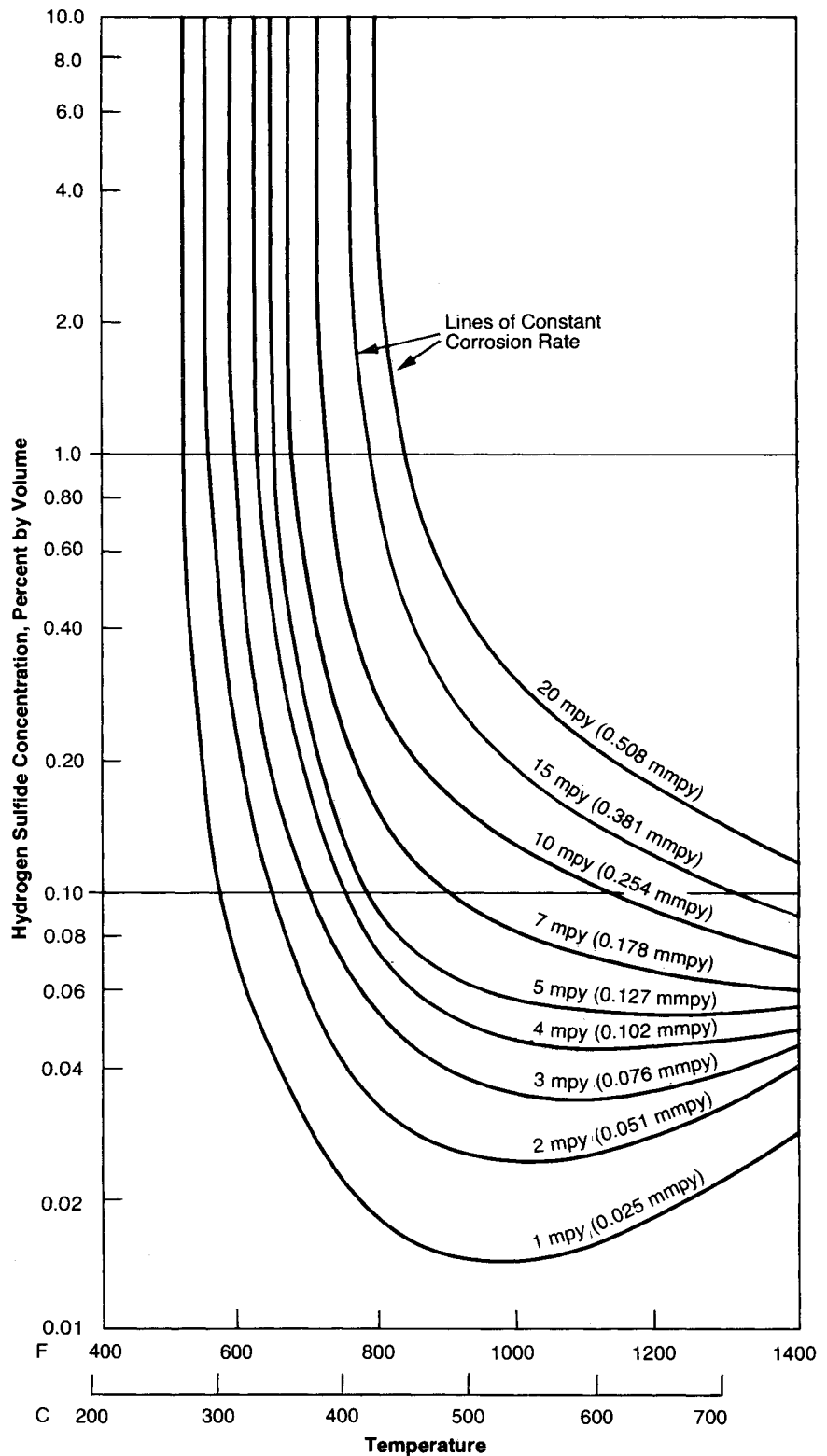
Effect of temperature and hydrogen sulfide concentration on corrosion rate of chromium-nickel austenitic stainless steels in hydrogen atmospheres at 175 to 500 psig (1.21-3.45 MPa). (Exposure time greater than 150 hr.)

Table 8						
Corrosion Rates of Stainless Steels in Air, Oxidizing and Reducing Flue Gases* (20)						
AISI Type	Air (mpy)		Oxidizing Flue Gas (mpy) 2000°F		Reducing Flue Gas (mpy) 2000°F	
	2000°F	2200°F	5gS†	100gS	5gS	100gS
309	40-90	60	50-70	40-100	20-50	30
310	40	50-80	50	40	20-50	30
330	50	100-1000	60-300	100-500	50-200	300-800

*Data for cast stainless steels. †Grains of sulfur per 100 cu ft.

Table 9			
Pack Carburization Test* (21)			
AISI Type	Composition	Si Content (%)	Increase in Bulk Carbon Content (%)
330	15 Cr-35 Ni	0.47	0.23
330	15 Cr-35 Ni + Si	1.00	0.08
310	25 Cr-20 Ni	0.38	0.02
314	25 Cr-20 Ni + Si	2.25	0.03
309	25 Cr-1 2Ni	0.25	0.12
347	18 Cr-8 Ni + Cb	0.74	0.57
321	18 Cr-8 Ni + Ti	0.49	0.59
304	18 Cr-8 Ni	0.39	1.40
302B	18 Cr-8 Ni + Si	2.54	0.22
446	28 Cr	0.34	0.07
430	16 Cr	0.36	1.03

*40 Cycles of 25 hours at 1800°F

Carburization

Carburization is the diffusion of carbon into a metal. It can be carried to such a degree as to form high-carbon alloys with low ductility and impact strength at ambient temperature. The chromium carbides thus formed are prone to rapid oxidation under oxidizing conditions and the virtual disappearance of the metal carbides, leaving deep holes. Such an extension of carburization, which is relatively uncommon, is known as metal dusting.

Carburization can be caused by continous overheating of a metal in the presence of hydrocarbon gases, carbon monoxide, coke, or molten metals containing dissolved carbon.

Laboratory and field experience indicate that the rate of carburization is affected by chromium content. For example, a comparison of the carbon absorbed by Type 430, on the one hand, and Type 446 under identical conditions – Table 9 – shows that in the higher chromium alloy the diffusion rate is much slower. Higher nickel content is also effective in slowing diffusion rate, such as in Type 310 compared to Types 309 or 304. Silicon is also effective in preventing carbon absorption, such as in Types 302B and 314.

Hydrogen Attack

Atomic hydrogen, which results from a corrosion reaction or the dissociation of molecular hydrogen, can diffuse rapidly through the steel lattice to voids, imperfections, or low-angle grain boundaries. The diffusing atoms accumulate and combine to form molecular hydrogen or, at high temperature, react with carbon to form methane. The larger hydrogen or methane molecules are trapped, and the subsequent pressure buildup results in blisters or laminations (hydrogen damage) and/or degradation of ductility (hydrogen embrittlement). Eventually the steel cracks and may become unsuitable for continued use.

In low-temperature environments, carbon or low-alloy steels are usually suitable, but for temperatures above 800°F (427°C) and at high pressures (about 10,000 psi (68.9 MPa)) the austenitic stainless steels have sufficient chromium to impart good resistance to hydrogen attack. Nelson, in a comprehensive survey of all available service data, demonstrated that increasing chromium contents in steel permit higher operating temperatures

Figure 40
Safe Operating Zones for Steels in Hydrogen Service (22)
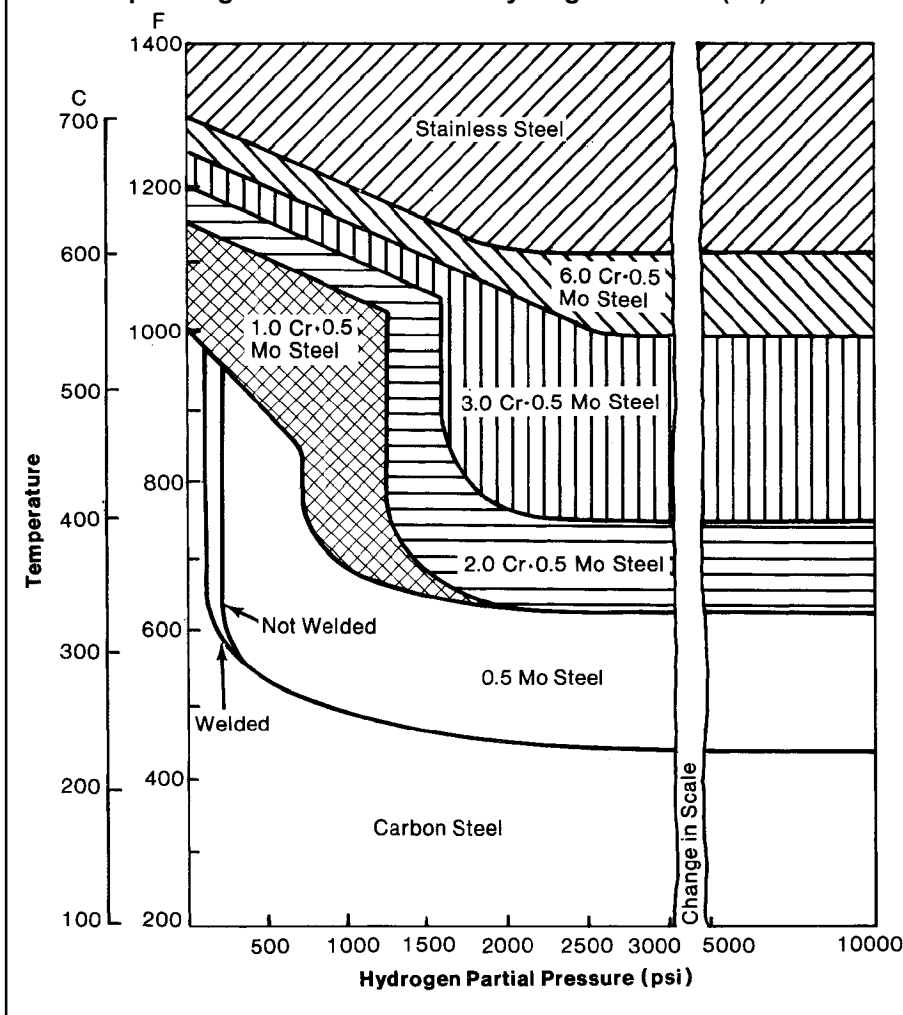
Figure 41
Corrosion of 18 - 8 Stainless Steel in Wet and Dry Chlorine Gas (24)
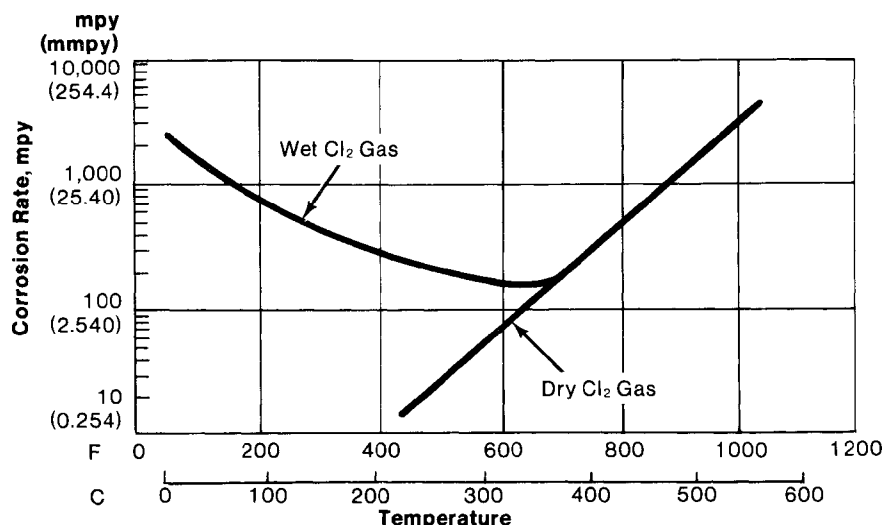
Table 10
Corrosion Rates of Stainless Steel in Ammonia Converter and Plant Line (22)

AISI Type	Nominal Ni Content %	Corrosion Rate (mpy)	
		Ammonia † Converter	Ammonia** Plant Line
446	–	1.12	164.5
430	–	0.9	–
302B	10	0.73	–
304	9	0.59	99.5
316	13	0.47	>520
321	11	0.47	–
309	14	0.23	95
314	20	0.1	–
330	34	0.06	–
330	36	0.02	–

†5-6% NH_3: 29,164 hr at 915-1024°F
**99.1% NH_3: 1540 hr at 935°F.

and hydrogen partial pressure (Figure 40).

Ammonia (and Nitrogen)

Most metals and alloys are inert towards molecular nitrogen at elevated temperature. However, atomic nitrogen will react with and penetrate many steels, producing hard, brittle nitride surface layers. One of the principal sources of atomic nitrogen is the dissociation of ammonia in ammonia converters and nitriding furnaces that operate in the temperature range of 700 to 1100°F (371 to 593°C) at pressures varying from atmospheric to 15,000 psi (103.4 MPa). In these atmospheres low-chromium steels may blister and/or crack. With chromium content exceeding 12%, these problems do not occur. Accordingly, the stainless steels are used safely for high-temperature service in hot ammonia atmospheres The behavior of stainless steels in ammonia depends on temperature, pressure, gas concentration, and chromium and nickel contents. Results from service tests have demonstrated that corrosion rates for straight-chromium stainless steels are greater than those for the chromium-nickel grades. Corrosion rates for several stainless steels exposed in an ammonia converter and plant line are shown in Table 10.

Halogens

Austenitic stainless steels are severely attacked by halogen gases at elevated temperatures. Fluorine is more corrosive than chlorine, and the upper temperature limits for dry gases are approximately 480°F and 600°F (249°C and 316°C), respectively, for the high chromium-nickel grades, as shown by Tables 11 and 12. Wet chlorine gas containing 0.4% water is more corrosive than dry chlorine up to about 700°F (371°C) as shown in Figure 41.

Table 11
Corrosion of Stainless Steels by Dry Chlorine and Hydrogen Chloride at High Temperatures (24)

Gas	Type	Approximate Temperature, F for given Corrosion Rate				
		30 mpy	60 mpy	120 mpy	600 mpy	1200 mpy
Chlorine	316	600	650	750	850	900
Chlorine	304	550	600	650	750	850
Hydrogen Chloride	316	700	700	900	1,100	1,200
Hydrogen Chloride	309 Cb	650	750	850	1,050	1,150
Hydrogen Chloride	304	650	750	850	1,100	1,200

Table 12
Corrosion of Stainless Steels by Dry Fluorine at High Temperature (25)

Type	Corrosion Rate, mpy at Various Temperatures								
	390°F	480°F	570°F	660°F	750°F	840°F	930°F	1080°F	1200°F
347	Nil	1,700	2,500	6,100	9,500	–	–	–	–
309 Cb	Nil	Nil	900	5,500	7,900	–	–	–	–
310	Nil	Nil	370	410	6,700	–	–	–	–
Nickel	–	–	–	–	8	23	60	350	190

Figure 42
Various Steps Through Which Metallic Atoms Must Go in Temperature Gradient Mass Transfer (26)

Hot Leg

If there is Selective Removal of a Constituent in Alloy, it must Diffuse to Surface

Solution Step

Diffusion Through Lamellar Layer

Carried to Cold Portion of System

Cold Leg

Supersaturation

Nucleation

Growth to stable crystal size

or

Supersaturation and Diffusion Through Lamellar Layer

Nucleation and Growth on Metallic Wall (or Diffusion into Wall)

Table 13 Corrosion of Stainless Steels by Liquid Sodium at 932°F (27)	
Type	Corrosion Rate*, mpy
303	<0.1
304	<0.1
321	<0.1
347	<0.1

* Based on one month static test with 5 micron sodium with about 0.005-0.01 wt % oxygen using stainless steel vessels.

Liquid Metals

Liquid-metal corrosion differs from aqueous and gaseous corrosion since it depends primarily on the solubility of the solid metal in the liquid metal instead of on electro-chemical forces. Although chemical reactions may play an important role in liquid-metal corrosion, mass transfer mechanisms are the most significant. The major types of mass transfer and chemical corrosion by liquid metals are:

1) Simple solution – alloying
2) Temperature gradient mass transfer
3) Concentration gradient

(dissimilar-metal) mass transfer
4) Impurity reactions.

In the simple solution type of corrosion, solid metal dissolves in the liquid metal to its solubility limit. The result is either uniform thinning or deep intergranular penetration if a single constituent is preferentially leached from the solid metal. Alternately, the liquid metal may alloy with the container material to form undesirable brittle phases.

Temperature gradient mass transfer can occur when hot and cool zones exist in a liquid metal system. In essence, the solid metal dissolves in the hot zone and precipitates on the walls in the cool zone where its solubility is lower. Figure 42

illustrates the steps in temperature gradient mass transfer attack. This type of attack usually occurs as uniform corrosion and is often not as serious a problem as the plugging of orifices such as heat exchanger tubes that may occur in the cool zone.

If dissimilar metals are in contact with the same liquid metal, one of the metals may be transferred through the liquid metal to alloy with the other metal. Since this reaction continuously removes the soluble metal from solution, saturation is not attained, and corrosion can continue to destruction. An example of this type of attack is the rapid dissolution of Type 304 by liquid lithium in an iron container. Figure 43 is a schematic view of the manner in which dissimilar mass transfer occurs.

Relatively small amounts of impurities such as oxygen, nitrogen and carbon may greatly affect the rate of liquid-metal corrosion. The precise action of the impurities varies with the system and is not completely understood. Some studies showed that impurities:

1) may change the solubility limit
2) may participate in some intermediate chemical reaction essential to permit the solid metal to cross the interface
3) may affect the wetting tendencies of the liquid metal
4) may form a barrier to the reaction.

Thus impurities are not necessarily harmful, and in several liquid-metal systems the introduction of controlled quantities of the proper impurities has reduced the corrosion rates to tolerable levels.

FACTORS AFFECTING LIQUID-METAL CORROSION – Some of the factors affecting liquid-metal corrosion, such as temperature and temperature gradient, have already been mentioned. Other important factors include temperature fluctuation, velocity of flow, and the ratio of surface area to liquid volume. The

Figure 43
Schematic View of the Manner in Which Dissimilar Metal Mass Transfer Occurs (26)

Metal A

Solution

Movement by Diffusion or Liquid Movement

Metal B

Diffusion Into Metal B and Alloy Formation

Table 14
Corrosion of Stainless Steels by Liquid NaK at Elevated Temperatures (28)

Type	Na in NaK, wt %	Temperature, °F	Test Duration, hr	Corrosion Rate,* mpy
302	56	390	144	0.1
302	56	1110	144	G**
303	56	1110	144	0.3
304	20	1400	200	0.6
304	56	1520	500	1
316	56	1110	144	G**
316	20	1400	200	0.2
321	20	1000	200	0.5
347	56	390	144	<0.1
347	56	1110	144	G**
310	56	1110	144	G**
310	20	1400	200	0.8

* Tests run under static conditions.
** G indicates specimens gained weight, from 0.1 to 0.7 mg/sq cm/mo

ratio of surface area to liquid volume is perhaps the most important and the least obvious. This ratio is important because the greater the liquid volume the greater will be the amount of solid metal that can be held in solution. Therefore, as the ratio of the surface area to liquid volume decreases, the amount of corrosion increases.

CORROSION BY SPECIFIC LIQUID METALS – The corrosion resistance of austenitic stainless steels to various liquid metals cannot be generalized, so some of the low-melting metals and alloys are discussed separately:

Sodium and Sodium-Potassium Alloys – The austenitic stainless steels have been used extensively to contain sodium and sodium-potassium alloys (NaK). They are not susceptible to mass transfer up to 1000°F (538°C), and the rate of transfer remains within moderate levels up to 1600°F (871°C). Tables 13 and 14 summarize the behavior of a number of stainless steels in contact with sodium and NaK, respectively. The stainless steels and high-nickel alloys are probably the best available structural materials in dynamic sodium test systems, providing the hot-zone temperature of the system does not exceed 1200°F (649°C) and the temperature differential does not exceed 300°F (149°C).

The stainless steels are sensitive to oxygen contamination in liquid sodium. If the oxygen content exceeds about 0.02%, the corrosion rate increases markedly, as shown in Figure 44. Above about 0.1 % oxygen, sodium oxide will attack stainless steels intergranularly and form a brittle surface layer.

Molten sodium may cause severe

carburization of stainless steels if it becomes contaminated by carbonaceous material. For example, carburization has occurred from the storage of the liquid metal under kerosene.

Lead – Mass transfer will be experienced to varying degrees with any of the common engineering alloys exposed to molten lead under dynamic conditions. In addition, lead is an active corrodent in static systems. Lead has a comparatively high solubility for a number of metals, and therefore simple solution attack may result in serious deterioration even in the absence of mass transfer. Further, lead absorbs oxygen readily and may cause rapid oxidation of susceptible alloys, particularly at the interface in an open pot where oxygen contamination is high. In some instances when the lead bath has been maintained in a reduced state by the introduction of a hydrocarbon, carburization of stainless

Figure 44
Effect of Oxygen on the Corrosion of Type 347 Stainless Steel in Liquid Sodium (29)

27
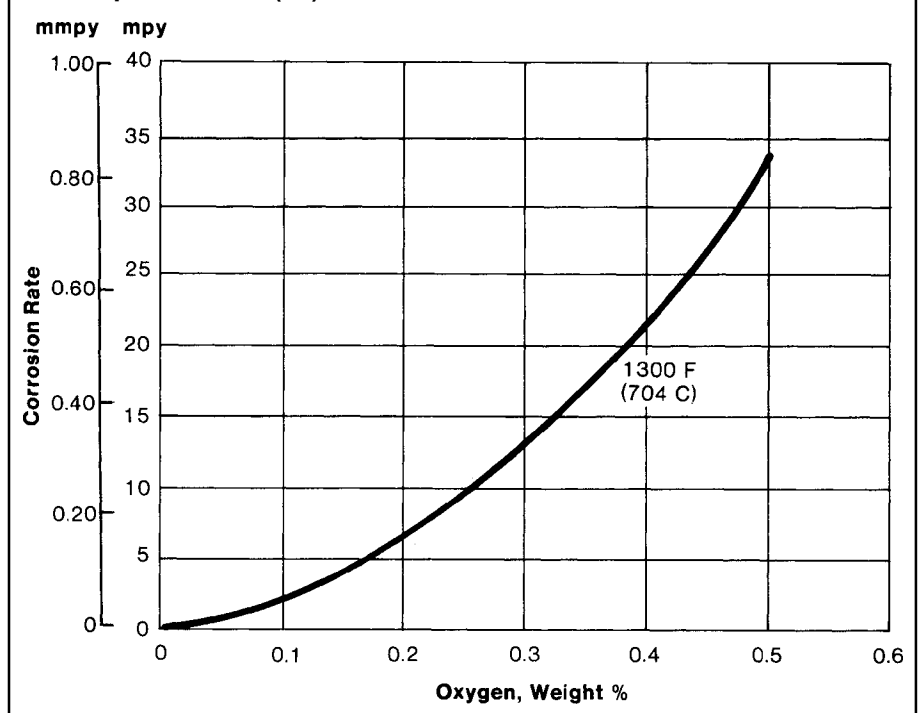
Figure 45
Qualitative Resistance of Stainless Steels and Nickel in Liquid Lead at 1442°F in Thermal Convection Loop (Gradient 540°F) (30)
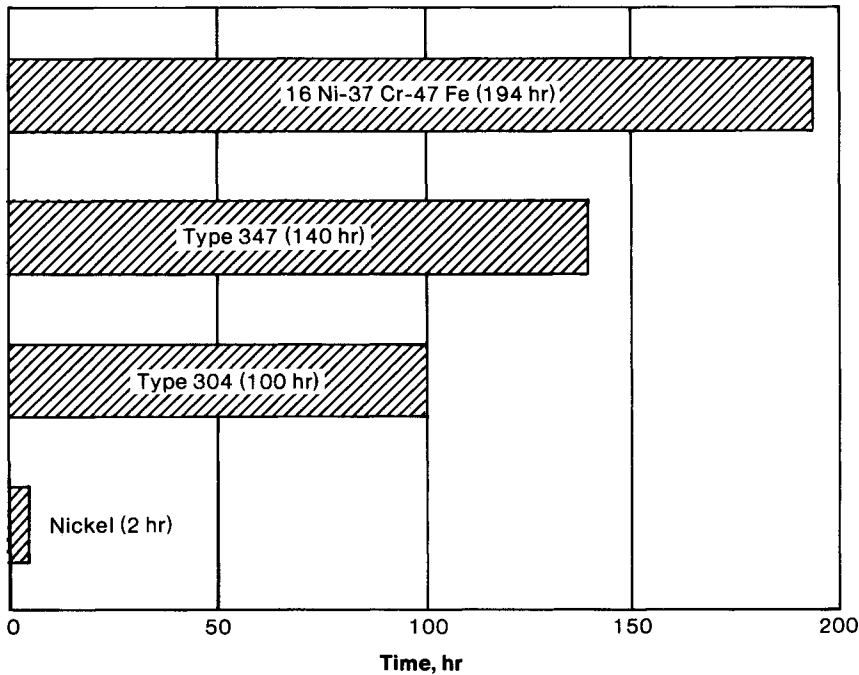
steel containers has resulted. Figure 45 summarizes the test results for stainless steel tubes inserted in a quartz thermal convection loop containing molten lead. The data are based on the time required for plugging the half-inch diameter tubes in the cold leg. This criterion, however, does not always accurately reflect the extent of deterioration of the samples.

Other Low-Melting Metals – Molten metals and alloys such as aluminum, zinc, antimony, bismuth, cadium, tin, lead-bismuth, and lead-bismuth-tin are generally corrosive to stainless steels. Table 15 indicates the corrosion resistance of stainless steels to these metals and several others and includes data on the type of attack that occurs and the maximum allowable operating temperatures.

Molten Salts

Molten salts may corrode metals according to the reaction processes described for liquid-metal corrosion, namely, simple solution, temperature and concentration gradient mass transfer, and impurity reactions. Corrosion may also occur by direct chemical reaction, or

Table 15
Corrosion of Stainless Steels by Other Liquid White Metals (27)

Molten Metal	Container Metal Type	Resistance of Container Metal
Lithium	302, 303, 304, 316, 347	Resistant to 600°F
Magnesium	All types	Attacked at 1204°F
Thallium	All types	Resistant to 1200°F
Cadmium	All types	Poor resistance at its melting point, 1200°F
Zinc	All types	Poor at 930°F; embrittlement above about 1372°F
Antimony	All types	Poor resistance to antimony. Resistant to cadmium alloys with over 50% antimony to 185°F above liquidus.
Mercury	304 310	20 mpy at 1210°F 47 mpy at 1210°F
Aluminum	All types	Embrittlement penetration at melting point, 1220°F
Gallium	347 All types	Satisfactory to 390°F Severe alloying at 1110°F
Indium	304	Superficial attack at 1200°F
Bismuth	347 All types	Minor attack up to 1500°F Good up to 500°F
Bismuth-Lead Alloy (Eutectic 55.5% Bi, 44.5% Pb)	304 317 310	Gained wt at 900°F; 7.2 mpy at 1200°F* 1.8 mpy at 1200°F* 0.2 mpy at 900°F; gained wt at 1200°F*
Bismuth-Lead-Tin Alloy (Eutectic 52% Bi, 32% Pb, 16% Sn)	304 317 310	2.4 mpy at 1200°F* 3.9 mpy at 1200°F* 7.8 mpy at 1200°F*
Tin	All types	Short time use at melting point, 450°F

*Everhart and Van Nuis (31)

Figure 46
Effect of Nickel Content on the Corrosion of Cast Nickel-Chromium Steels in Salt Bath at 1600°F (32)

(Bath consists of 55% BaCl$_2$, 25% KCl, and 20% NaCl)
Average of Seven Tests
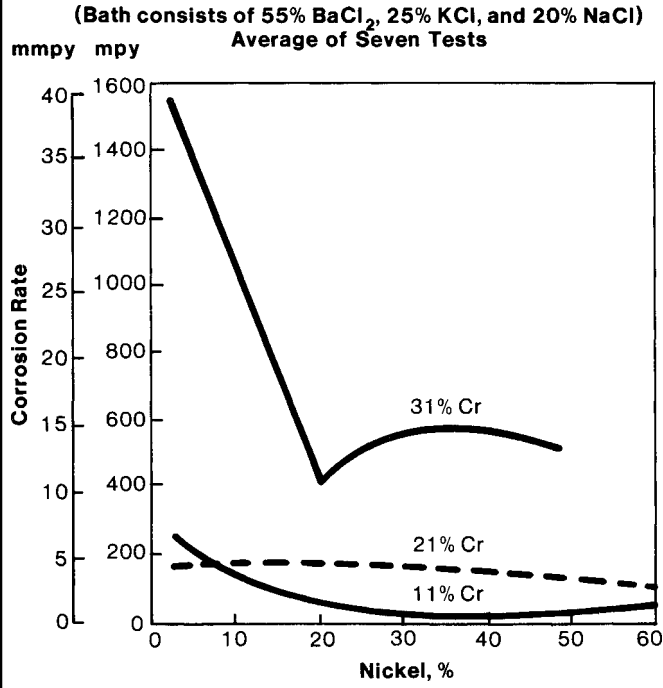
Figure 47
Effect of Nickel Content on the Intergranular Corrosion of Cast Nickel-Chromium Steels in Salt Bath at 1600°F. (32)

(Bath consists of 55% BaCl$_2$, 25% KCl, and 20% NaCl)
Average of Seven Tests
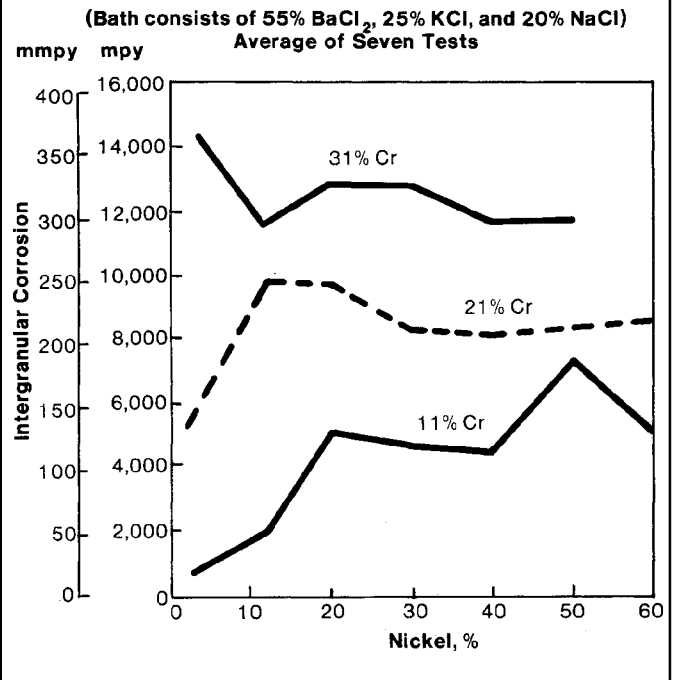
a combination of corrosion and the reaction processes. Most information available concerns the corrosive nature of heat treating salts or salt mixtures.

Chloride Salts – Barium, potassium and sodium chloride alone or in combination are common heat treating salts for use at elevated temperature. When pure, they are not particularly corrosive but may become increasingly corrosive as they are contaminated or oxidized during service. Studies on cast stainless steels and high-nickel alloys exposed to typical heat treating salts were made using a ternary salt mixture consisting of 55% barium chloride, 25% potassium chloride and 20% sodium chloride at 1600°F (871°C). The results, as illustrated in Figure 46, show that the resistance of the cast alloys, in general, increases with nickel content. The effect of nickel on the resistance to intergranular attack, however, is irregular as suggested by Figure 47. Stainless steels high in nickel and low in chromium, such as Type 330, are usually selected for chloride salt containments.

Nitrate and Nitrate Salts – For lower-temperature heat treating (300 to 1100°F) (149 to 593°C), mixtures of potassium nitrate and sodium nitrate are frequently used. While cast iron or steel are service-able for temperatures below 800°F (427°C), the austenitic stainless steels show excellent resistance at the upper service temperatures, as suggested by Table 16.

Cyanide Salts – Molten cyanide salt baths are used widely to surface-harden mild or low-alloy steels by the formation of a carburized, nitrified, or carbonitrided layer on the surface. Since a chemical reaction is an essential part of the process, these salts are more corrosive than the salts used purely as heat transfer media. As discussed earlier, chromium inhibits carburization but promotes nitridation. Nickel, however, inhibits both reactions, therefore, stainless steels with low chromium and high nickel – Type 330 for example – are used in this service. The nitrogen and carbon penetration for several stainless steels are given in Table 17.

Table 16
Corrosion Resistance of Stainless Steels to Molten Potassium Nitrate at 860-970 F (32)

Type	Corrosion Rate,* mpy	Depth of Intergranular attack**, mils
330	0	2.4
310	0	0
314	0	0.1
309	<1.2	0.1
321	0	0.1
347	<1.2	0.1
304	0	0.1
302B	0	0.2

* Based on micrometer measurements after 6944 hr exposure.
** Based on microscopic examination after 6944 hr exposure.

Table 17
Corrosion of Stainless Steels by Cyanide Heat Treating Salt (32)

Type	Depth of Nitrogen Penetration, mils	Depth of Carburization, mils
330	8	33
330 + Si	5.5	33
310	10.5	33
314	20	30
309	14	39
316	21.5	62
321	19	59
304	18	52
302 B	42.5	56
60 Ni-15 Cr	2.5	21

Note: Salt composition was 23-30% NaCN, 2-7% NaOCN, 0.6-1.5% NaCl, Bal Na$_2$CO$_3$; 672 hr exposure at 1300-1500°F.

29

Fuel Ash

When stainless steels and other metals or alloys are heated in the presence of certain low-melting point metallic oxides, corrosion occurs at an extremely rapid rate, which is referred to as catastrophic oxidation. Catastrophic oxidation has received much attention with the growing use of low-grade fuels.

Severe corrosion may be encountered during combustion of these fuels if ash or molten salts are deposited on hot metal surfaces. Ash, as deposited or in combination with other available materials including the scale itself, can form a molten phase capable of fluxing a previously protective scale, permitting destructive corrosion to occur.

Vanadium pentoxide, by itself or in mixtures with sodium sulfate in fuel ash, is the most serious cause of this type of corrosion. Fuels containing only 50 parts per million vanadium can produce severe attack on stainless steels, as illustrated in Figure 48.

Chlorides present in amount as little as 0.3% with sulfates present can also produce severe corrosion, but the attack is usually not as severe as from vanadium salts.

All of the stainless steels and all other common engineering alloys are severely attacked by fuel ash containing vanadium or chlorides with or without sulfates. Methods of preventing this type of attack, therefore, are directed toward removing the contaminants from the fuel, or making additions to the fuel to raise the fusion temperature of the ash. Calcium oxide and magnesium oxide additions have been useful in this direction.

Automotive Exhaust

The automotive exhaust environment is somewhat of an enigma because there are not clearly definable and consistent conditions on which to base material selection. Generally, automotive exhaust consists of a mixutre of carbon monoxide, oxides of nitrogen, unburned hydrocarbons, and moisture. Temperatures run the gamut from ambient to 1800°F Gas velocities are high; the internal combustion engine causes pulsation of the gas stream and vibration of the equipment; and operation is highly cyclic. The problem is further exacerbated by the different levels of expertise on the part of owners and mechanics servicing the engine, which results in operating conditions that sometime exceed design expectations and anticipated temperatures.

Couple these conditions with the continuing commitment to tighten automotive emissions, at the same time reduce weight, and the exhaust system no longer resembles the systems of old – consisting essentially of cast manifold, pipe, and muffler.

While steel – either plain, galvanized, or aluminum coated - has served well, designers are now specifying stainless steels that are more capable of withstanding oxidation and corrosion at the higher temperatures experienced in these new systems, and considering alloys that also have good high-temperature strength.

For example, Type 409, often referred to as the muffler grade stainless steel, was one of the first to be used extensively in auto exhaust systems, particularly for catalytic converters, which are installed on most U.S.-made cars. Type 409 is also being used for many of the exhaust gas ducts in turbochargers, and it is a good candidate for mufflers and tail pipe components. For some applications, however, Type 409 may lack sufficient creep strength, in which case a more-highly alloyed stainless steel – such as one of the austenitic or new ferritic grades – might be more suitable. A typical example is a converter-turbocharger combination in which higher pressures result in increased temperatures.

Type 304L stainless steel is now being used extensively for exhaust gas coolers, which are small heat exchangers using engine coolant to lower the temperature of a small volume of exhaust gas recycled through the fuel intake. The cool inert gas helps to reduce oxides of nitrogen. The low-carbon grade is specified to prevent sensitization during high-temperature brazing of the cooler components during assembly.

As exhaust system engineers get closer to achieving a practical design for a fabricated sheet metal manifold, which will operate at temperatures higher than the cooler or catalytic converter, other stainless steels,or even high-nickel alloys, are being considered.

In summary, exhaust system development programs are in full swing at all automotive companies and component manufacturers, and a wide range of alloys are under consideration, including some that are only in early stages of commercial development. (34) (35) (36)

Figure 48
Effect of Sodium Sulfate–Vanadium Pentoxide Mixtures on Type 304 Stainless Steel (33)
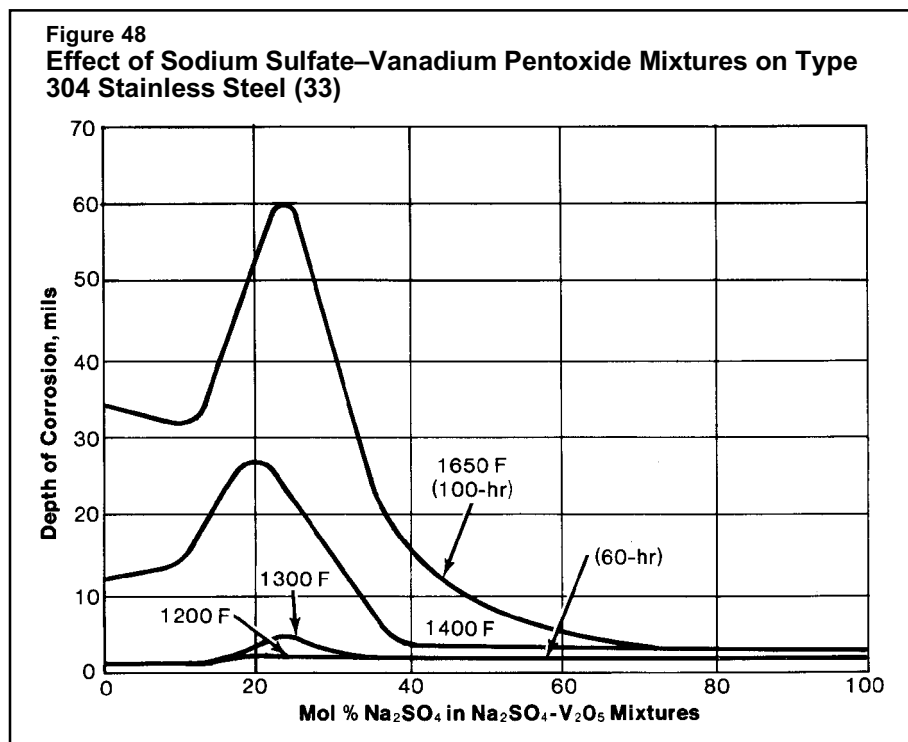
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HIGH-TEMPERATURE DATA

The tables following show typical physical and mechanical properties of eight stainless steels frequently used for high-temperature service. Space does not permit publication of data on all stainless steels. However, readers may obtain data sheets containing similar information on specific types by sending a request (with a self-addressed envelope) to the following address:

Committee of Stainless Steel
  Producers
American Iron and Steel Institute
100016th Street N.W.
Washington, D.C. 20036

Additional high-temperature data sheets are available on the following stainless steels ana nigh-temperature alloys:

AISI Types

Austenitic		Ferritic	Martensitic
201	305	405	403
202	309S	409	416
301	310S	430F	420
302	316L	430F Se	
302B	316N	442	
303	317	446	
304L	330		
304N	348		

High-Temperature Alloys

800	X-750
801	718
600	18-18-2
601	216
625	E-Brite 26-1
X	21-6-9
20Cb-3	20-45-5
A-286	700
18-18 Plus	Nitronic 50
Pyromet 31	18-2(444)

The data in the following tables and in the data sheets available on request are typical values and are intended as general information only. For design purposes it is recommended that reference be made to appropriate standards and specifications, such as those prepared by ASME and ASTM. *(Source of the data are various stainless steel industry publications.)*

TYPE 410 S41000

CHEMICAL COMPOSITION, (Maximum unless noted otherwise)											
C	Mn	P	S	Si	Cr	Ni	N	Mo	Ti	Al	Cb + Ta
0.15	1.00	0.040	0.030	1.00	11.50/ 13.50						

REPRESENTATIVE MECHANICAL PROPERTIES
(Annealed sheet unless noted otherwise)

Test Temperature		Yield Strength 0.2% Offset		Tensile Strength		Elongation in 2" (50.80mm)	Reduction of Area	Hardness Rockwell
°F	°C	ksi	MPa	ksi	MPa	%	%	B
80	27	45	310	70	483	25		80
300	149	36	248	74	510	36	79	
400	204	135*	931	150*	1034			
500	260	33	228	70.5	486	33	79	
600	316	125*	862	145*	1000			
700	371	30	207	62.5	431	33	77	
800	427	115*	793	130*	896			
900	482	26.7	184	52.5	362	41	83	
1000	538	95*	655	100*	689			
1100	593	23	159	33	228	57	95	
1200	649	40*	276	45*	310			
1300	704	9.5	66	15.2	105	73	98	
1400	760	14*	97	18*	124			
1500	816			9	62	80	97	
1600	871	10*	69	15*	103			

*Heat Treated

REPRESENTATIVE CREEP AND RUPTURE PROPERTIES

Test Temperature		Stress for a Creep Rate of				Stress for Rupture in			
		0.0001% per Hour (1% in 10,000 Hours)		0.00001% per Hour (1% in 100,000 Hours)		1,000 Hours		10,000 Hours	
°F	°C	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
900	482	24	165	13.6	94	34	234	22	152
1000	538	9	62	7.4	51	19.4	134	13	90
1100	593	4.2	29	3.6	25	10	69	6.8	47
1200	649	2	14	1.7	12	4.8	33	2.8	19
1300	704	0.8	6	0.6	4	2.5	17	1.2	8
1400	760	–		–		1.2	8	0.6	4

EFFECT OF PROLONGED EXPOSURE AT ELEVATED TEMPERATURES

Representative Mechanical Properties at Room Temperature

100,000 Hours (Without Stress) Exposure Temp.		Yield Strength 0.2% Offset		Tensile Strength		Elongation in 2" (50.80mm)	Reduction of Area
°F	°C	ksi	MPa	ksi	MPa	%	%
900	482	42	290	78.4	541	30	66
1050	566	40.1	276	74.5	514	33	68
1200	649	37.8	261	69.4	478	35	69

PHYSICAL PROPERTIES

Thermal Conductivity

	Btu/hr/sq ft/ft/°F	W/m•K
212°F (100°C)—	14.4	0.174
932°F (500°C)—	16.6	0.201

Mean Coefficient of Thermal Expansion per Degree °F (°C) ($\times 10^6$)

32 to 212°F (0 to 100°C)— 5.5 (9.9)
32 to 600°F (0 to 315°C)— 6.3 (11.4)
32 to 1000°F (0 to 538°C)— 6.4 (11.6)
32 to 1200°F (0 to 649°C)— 6.5 (11.7)

Modulus of Elasticity

Temperature		Modulus	psi ($\times 10^6$)	GPa
°F	°C			
80	27	Tension	29.0	200

TYPE 430 S43000

CHEMICAL COMPOSITION, (Maximum unless noted otherwise)											
C	Mn	P	S	Si	Cr	Ni	N	Mo	Ti	Al	Cb + Ta
0.12	1.00	0.040	0.030	1.00	16.00/ 18.00						

REPRESENTATIVE MECHANICAL PROPERTIES
(Annealed sheet unless noted otherwise)

Test Temperature		Yield Strength 0.2% Offset		Tensile Strength		Elongation in 2" (50.80mm)	Reduction of Area	Hardness Rockwell
°F	°C	ksi	MPa	ksi	MPa	%	%	B
80	27	50	345	75	517	25		85
300	149	34	234	66	455	32	71	
500	260	33.5	231	62.5	431	30	72	
700	371	33	228	57.5	396	30	73	
900	482	27.5	190	48.5	334	35	75	
1100	593	19	131	30	207	42	88	
1300	704	7.2	50	15	103	82	93	
1500	816	5.5	38	7	48	83	99	
1700	927			3.5	24	98	98	
1900	1038			2	14	100	94	

REPRESENTATIVE CREEP AND RUPTURE PROPERTIES

Test Temperature		Stress for a Creep Rate of				Stress for Rupture in			
		0.0001% per Hour (1% in 10,000 Hours)		0.00001% per Hour (1% in 100,000 Hours)		1,000 Hours		10,000 Hours	
°F	°C	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
900	482	16	110	12	83	30	207	26	179
1000	538	9.1	63	6.4	44	16.7	115	13	90
1100	593	4.6	32	3.4	23	9	62	6.7	46
1200	649	2.4	17	1.7	12	5.1	35	3.5	24
1300	704	1.4	10	0.9	6	2.8	19	2	14
1400	760	1	7			1.6	11		
1500	816	0.6	4			0.9	6		

EFFECT OF PROLONGED EXPOSURE AT ELEVATED TEMPERATURES

Representative Mechanical Properties at Room Temperature

10,000 Hours (Without Stress) Exposure Temp.		Yield Strength 0.2% Offset		Tensile Strength		Elongation in 2" (50.80mm)	Reduction of Area
°F	°C	ksi	MPa	ksi	MPa	%	%
900*	482	92.6	638	113.6	783	21	59
1050	566	48.3	333	83.4	575	24	44
1200	649	38	262	68	469	29	64

* 100,000 Hours

PHYSICAL PROPERTIES

Thermal Conductivity

	Btu/hr/sq ft/ft/°F	W/m•K
212°F (100°C)—	15.1	0.182
932°F (500°C)—	15.2	0.183

Mean Coefficient of Thermal Expansion per Degree °F (°C) ($\times 10^6$)

32 to 212°F (0 to 100°C) — 5.8 (10.4)
32 to 600°F (0 to 315°C) — 6.1 (11.0)
32 to 1000°F (0 to 538°C) — 6.3 (11.4)
32 to 1200°F (0 to 649°C) — 6.6 (11.9)
32 to 1500°F (0 to 815°C) — 6.9 (12.4)

Modulus of Elasticity

Temperature		Modulus	psi ($\times 10^6$)	GPa
°F	°C			
80	27	Tension	29.0	200

TYPE 304 S30400

CHEMICAL COMPOSITION, (Maximum unless noted otherwise)											
C	Mn	P	S	Si	Cr	Ni	N	Mo	Ti	Al	Cb+Ta
0.08	2.00	0.045	0.030	1.00	18.00/ 20.00	8.00/ 10.50					

REPRESENTATIVE MECHANICAL PROPERTIES
(Annealed sheet unless noted otherwise)

Test Temperature		Yield Strength 0.2% Offset		Tensile Strength		Elongation in 2" (50.80mm)	Reduction of Area	Hardness Rockwell
°F	°C	ksi	MPa	ksi	MPa	%	%	B
80	27	42	290	84	579	55		80
300	149	26.4	182	68.4	472	50	77	
500	260	21.8	150	64.1	442	42	75	
700	371	19.5	134	61.9	427	38	73	
900	482	18.1	125	60	414	36	69	
1100	593	16.4	113	53.2	367	35	65	
1300	704	13.8	95	35	241	35	51	
1500	816	9.9	68	18	124	38	42	
1700	927	–		8.9	61	45	45	
1900	1038	–		4.8	33	88	69	
2000	1093	–		3.4	23	95	75	

REPRESENTATIVE CREEP AND RUPTURE PROPERTIES

Test Temperature		Stress for a Creep Rate of				Stress for Rupture in			
		0.0001% per Hour (1% in 10,000 Hours)		0.00001% per Hour (1% in 100,000 Hours)		1,000 Hours		10,000 Hours	
°F	°C	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
1000	538	25.5	176	17.9	123	49.8	343	36	248
1100	593	16.5	114	11.1	77	31	214	22.2	153
1200	649	10.8	74	7.2	50	19	131	13.8	95
1300	704	7	48	4.5	31	11.9	82	8.5	59
1400	760	4.6	32	2.9	20	7.7	53	5.3	37
1500	816	3	21	1.8	12	4.7	32	3.3	23

EFFECT OF PROLONGED EXPOSURE AT ELEVATED TEMPERATURES

Representative Mechanical Properties at Room Temperature

100,000 Hours (Without Stress) Exposure Temp.		Yield Strength 0.2% Offset		Tensile Strength		Elongation in 2" (50.80mm)	Reduction of Area
°F	°C	ksi	MPa	ksi	MPa		
900	482	34	234	85.1	587	67	74
1050	566	31.4	216	85.9	592	63	75
1200	649	32.3	223	85.2	587	58	64

PHYSICAL PROPERTIES

Thermal Conductivity

	Btu/hr/sq ft/ft/°F	W/m•K
212°F (100°C)—	9.4	0.113
932°F (500°C)—	12.4	0.149

Mean Coefficient of Thermal Expansion per Degree °F (°C) ($\times 10^6$)

32 to 212°F (0 to 100°C)— 9.6 (17.2)
32 to 600°F (0 to 315°C)— 9.9 (17.9)
32 to 1000°F (0 to 538°C)— 10.2 (18.4)
32 to 1200°F (0 to 649°C)— 10.4 (18.8)

Modulus of Elasticity

Temperature		Modulus	psi ($\times 10^6$)	GPa
°F	°C			
80	27	Tension	28.0	193
		Shear	12.5	86
200	93	Tension	27.9	192
		Shear	11.1	77
300	149	Tension	27.1	187
		Shear	10.8	74
400	204	Tension	26.6	183
		Shear	10.5	72
500	260	Tension	26.0	179
		Shear	10.2	70
600	316	Tension	25.6	177
		Shear	9.9	68
700	371	Tension	24.7	170
		Shear	9.7	67
800	427	Tension	24.1	166
		Shear	9.5	66
900	482	Tension	23.2	160
		Shear	9.2	63
1000	538	Tension	22.5	155
		Shear	8.9	61
1100	593	Tension	21.8	150
		Shear	8.6	59
1200	649	Tension	21.1	145
		Shear	8.3	57
1300	704	Tension	20.4	141
		Shear	8.0	55
1400	760	Tension	19.4	134
		Shear	7.7	53
1500	816	Tension	18.1	125
		Shear	7.4	51

TYPE 309 S30900

CHEMICAL COMPOSITION,
(Maximum unless noted otherwise)

C	Mn	P	S	Si	Cr	Ni	N	Mo	Ti	Al	Cb + Ta
0.20	2.00	0.045	0.030	1.00	22.00/ 24.00	12.00/ 15.00					

REPRESENTATIVE MECHANICAL PROPERTIES
(Annealed sheet unless noted otherwise)

Test Temperature		Yield Strength 0.2% Offset		Tensile Strength		Elongation in 2" (50.80mm)	Reduction of Area	Hardness Rockwell
°F	°C	ksi	MPa	ksi	MPa	%	%	B
80	27	45	310	90	621	45		85
300	149	35.2	243	80.3	554	48	70	
500	260	33.2	229	77	531	45	67	
700	371	30.8	212	74	510	42	64	
900	482	27.8	192	69	476	39	57	
1100	593	24.8	171	60	414	37	43	
1300	704	21.6	149	43	296	36	49	
1500	816	18.2	125	27	186	38	42	
1700	927			16	110	45	43	
1900	1038			8.5	59	58	61	
2000	1093			4	28	71	73	

REPRESENTATIVE CREEP AND RUPTURE PROPERTIES

Test Temperature		Stress for a Creep Rate of				Stress for Rupture in			
		0.0001% per Hour (1% in 10,000 Hours)		0.00001% per Hour (1% in 100,000 Hours)		1,000 Hours		10,000 Hours	
°F	°C	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
800	427	36.5	252	25.5	176				
900	482	23	159	16.1	111	60	414	55	379
1000	538	16	110	10.4	72	42	290	36.6	252
1100	593	11	76	7	48	29.2	201	24.5	169
1200	649	7	48	4.2	29	19.2	132	14.3	99
1300	704	4	28	2	14	11	76	7.7	53
1400	760	2	14	1	7	6.8	47	4.3	30
1500	816	1	7	0.4	3	4.1	28	2.5	17

EFFECT OF PROLONGED EXPOSURE AT ELEVATED TEMPERATURES

Representative Mechanical Properties at Room Temperature

10,000 Hours (Without Stress) Exposure Temp.		Yield Strength 0.2% Offset		Tensile Strength		Elongation in 2" (50.80mm)	Reduction of Area
°F	°C	ksi	MPa	ksi	MPa	%	%
900	482	34.4	237	83.3	574	62	78
1050	566	36.1	249	86.9	599	57	66
1200	649	34.5	238	87.4	603	53	60

PHYSICAL PROPERTIES

Thermal Conductivity

	Btu/hr/sq ft/ft/°F	W/m•K
212°F (100°C)—	9.0	0.108
932°F (500°C)—	10.8	0.130

Mean Coefficient of Thermal Expansion per Degree °F (°C) ($\times 10^6$)

32 to 212°F (0 to 100°C) — 8.3 (15.0)
32 to 600°F (0 to 315°C) — 9.3 (16.6)
32 to 1000°F (0 to 538°C) — 9.6 (17.2)
32 to 1200°F (0 to 649°C) — 10.0 (18.0)
32 to 1800°F (0 to 981°C) — 11.5 (20.6)

Modulus of Elasticity

Temperature		Modulus	psi ($\times 10^6$)	GPa
°F	°C			
80	27	Tension	29.0	200
800	427	Tension	23.1	159
1000	538	Tension	22.6	156
1200	649	Tension	21.8	150
1300	704	Tension	21.2	146
1500	816	Tension	19.8	137
1600	871	Tension	19.2	132

TYPE 310 S31000

CHEMICAL COMPOSITION, (Maximum unless noted otherwise)											
C	Mn	P	S	Si	Cr	Ni	N	Mo	Ti	Al	Cb + Ta
0.25	2.00	0.045	0.030	1.50	24.00/ 26.00	19.00/ 22.00					

REPRESENTATIVE MECHANICAL PROPERTIES
(Annealed sheet unless noted otherwise)

Test Temperature		Yield Strength 0.2% Offset		Tensile Strength		Elongation in 2" (50.80mm)	Reduction of Area	Hardness Rockwell
°F	°C	ksi	MPa	ksi	MPa	%	%	B
80	27	45	310	95	655	45		85
300	149	34.9	241	82.1	566	38	69	
500	260	32.5	224	77.6	535	35	63	
700	371	29.6	204	75.5	521	35	57	
900	482	26.3	181	69.5	479	35	53	
1100	593	22.7	157	61.5	424	38	47	
1300	704	19	131	45.5	314	31	42	
1500	816	15	103	29.5	203	30	38	
1700	927			17	117	49	48	
1900	1038			11	76	56	46	
2000	1093			7	48	57	48	

REPRESENTATIVE CREEP AND RUPTURE PROPERTIES

Test Temperature		Stress for a Creep Rate of				Stress for Rupture in			
		0.0001% per Hour (1% in 10,000 Hours)		0.00001% per Hour (1% in 100,000 Hours)		1,000 Hours		10,000 Hours	
°F	°C	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
900	482	22.8	157	15	103				
1000	538	17.6	121	11.8	81	37.6	259	32.4	223
1100	593	12.8	88	8.8	61	23.6	163	20	138
1200	649	8.4	58	6	41	13.4	92	11	76
1300	704	5	34	3.7	25	8.7	60	6.9	48
1400	760	2.4	17	2	14	6	41	4.5	31
1500	816	1	7	0.8	6	4.5	31	3.3	23

EFFECT OF PROLONGED EXPOSURE AT ELEVATED TEMPERATURES

Representative Mechanical Properties at Room Temperature

10,000 Hours (Without Stress) Exposure Temp.		Yield Strength 0.2% Offset		Tensile Strength		Elongation in 2" (50.80mm)	Reduction of Area
°F	°C	ksi	MPa	ksi	MPa	%	%
900	482	37.2	256	90.2	622	54	69
1050	566	42.3	292	93.5	645	46	54
1200	649	58.1	401	117.9	813	4	4

PHYSICAL PROPERTIES

Thermal Conductivity

	Btu/hr/sq ft/ft/°F W/m•K	
212°F (100°C)—	8.2	0.099
932°F (500°C)—	10.8	0.130

Mean Coefficient of Thermal Expansion per Degree °F (°C) ($\times 10^6$)

32 to 212°F (0 to 100°C)— 8.8 (15.9)
32 to 600°F (0 to 315°C)— 9.0 (16.2)
32 to 1000°F (0 to 538°C)— 9.4 (17.0)
32 to 1200°F (0 to 649°C)— 9.7 (17.5)
32 to 1800°F (0 to 981°C)— 10.6 (19.1)

Modulus of Elasticity

Temperature		Modulus	psi ($\times 10^6$)	GPa
°F	°C			
80	27	Tension	29.0	200
200	93	Tension	28.2	194
		Shear	10.9	75
300	149	Tension	27.5	190
		Shear	10.6	73
400	204	Tension	26.8	185
		Shear	10.3	71
500	260	Tension	26.2	181
		Shear	10.0	69
600	316	Tension	25.5	176
		Shear	9.7	67
700	371	Tension	24.9	172
		Shear	9.4	65
800	427	Tension	24.2	167
		Shear	9.1	63
900	482	Tension	23.6	163
		Shear	8.8	61
1000	538	Tension	23.0	159
		Shear	8.5	59
1100	593	Tension	22.4	154
		Shear	8.2	57
1200	649	Tension	21.8	150
		Shear	7.9	54
1300	704	Tension	21.2	146
		Shear	7.6	52
1400	760	Tension	20.5	141
		Shear	7.2	50
1500	816	Tension	19.0	131
		Shear	6.9	48
1600	871	Tension	19.2	132
		Shear	6.6	46

TYPE 316 S31600

CHEMICAL COMPOSITION, (Maximum unless noted otherwise)											
C	Mn	P	S	Si	Cr	Ni	N	Mo	Ti	Al	Cb + Ta
0.08	2.00	0.045	0.030	1.00	16.00/ 18.00	10.00/ 14.00		2.00/ 3.00			

REPRESENTATIVE MECHANICAL PROPERTIES
(Annealed sheet unless noted otherwise)

Test Temperature		Yield Strength 0.2% Offset		Tensile Strength		Elongation in 2" (50.80mm)	Reduction of Area	Hardness Rockwell
°F	°C	ksi	MPa	ksi	MPa	%	%	B
80	27	42	290	84	579	50		79
300	149	29.2	201	75	517	53	77	
500	260	25	172	73	503	49	75	
700	371	23	159	72.5	500	47	69	
900	482	21.5	148	70.2	484	47	69	
1100	593	20.3	140	65.5	452	44	63	
1300	704	19	131	50	345	43	58	
1500	816	16	110	27	186	42	55	
1700	927			11.6	80	67	60	
1900	1038			5.6	39	60	47	
2000	1093			4	28	75	55	

REPRESENTATIVE CREEP AND RUPTURE PROPERTIES

Test Temperature		Stress for a Creep Rate of				Stress for Rupture in			
		0.0001% per Hour (1% in 10,000 Hours)		0.00001% per Hour (1% in 100,000 Hours)		1,000 Hours		10,000 Hours	
°F	°C	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
1000	538	35.5	245	20.1	139	50	345	43	296
1100	593	22.5	155	12.4	85	34	234	26.5	183
1200	649	14.2	98	7.9	54	23	159	16.2	112
1300	704	8.9	61	4.8	33	15.4	106	9.9	68
1400	760	5.6	39	3	21	10.3	71	6	41
1500	816	3.6	25	1.9	13	6.7	46	3.7	26

EFFECT OF PROLONGED EXPOSURE AT ELEVATED TEMPERATURES

Representative Mechanical Properties at Room Temperature

10,000 Hours (Without Stress) Exposure Temp.		Yield Strength 0.2% Offset		Tensile Strength		Elongation in 2" (50.80mm)	Reduction of Area
°F	°C	ksi	MPa	ksi	MPa	%	%
900*	482	45	310	91.9	634	60	73
1050	566	41.8	288	97.2	670	49	65
1200*	649	50.5	348	113	779	31	49

*100,000 Hours

PHYSICAL PROPERTIES				

Thermal Conductivity

	Btu/hr/sq ft/ft/°F	W/m•K
212°F (100°C)—	9.4	0.113
932°F (500°C)—	12.4	0.149

Mean Coefficient of Thermal Expansion per Degree °F (°C) ($\times 10^6$)

32 to 212°F (0 to 100°C)— 8.9 (15.9)
32 to 600°F (0 to 315°C)— 9.0 (16.2)
32 to 1000°F (0 to 538°C)— 9.7 (17.5)
32 to 1200°F (0 to 649°C)— 10.3 (18.6)
32 to 1500°F (0 to 815°C)— 11.1 (20.0)

Modulus of Elasticity

Temperature		Modulus	psi ($\times 10^6$)	GPa
°F	°C			
80	27	Tension	28.0	193
200	93	Tension	28.1	194
		Shear	11.0	76
300	149	Tension	27.5	190
		Shear	10.6	73
400	204	Tension	26.9	185
		Shear	10.3	71
500	260	Tension	26.3	181
		Shear	10.0	69
600	316	Tension	25.6	177
		Shear	9.7	67
700	371	Tension	24.9	172
		Shear	9.4	65
800	427	Tension	24.2	167
		Shear	9.1	63
900	482	Tension	23.5	162
		Shear	8.8	61
1000	538	Tension	22.8	157
		Shear	8.5	59
1100	593	Tension	22.2	153
		Shear	8.3	57
1200	649	Tension	21.5	148
		Shear	8.1	56
1300	704	Tension	20.8	143
		Shear	7.9	54
1400	760	Tension	20.0	138
		Shear	7.7	53
1500	816	Tension	19.1	132
		Shear	7.5	52

TYPE 321 S32100

CHEMICAL COMPOSITION, (Maximum unless noted otherwise)												
C	Mn	P	S	Si	Cr	Ni	N	Mo	Ti	Al	Cb + Ta	
0.08	2.00	0.045	0.030	1.00	17.00/ 19.00	9.00/ 12.00			5XC min.			

REPRESENTATIVE MECHANICAL PROPERTIES
(Annealed sheet unless noted otherwise)

Test Temperature		Yield Strength 0.2% Offset		Tensile Strength		Elongation in 2" (50.80mm)	Reduction of Area	Hardness Rockwell
°F	°C	ksi	MPa	ksi	MPa	%	%	B
80	27	35	241	90	621	45		80
300	149	27.5	190	68	469	52	70	
500	260	24.7	170	62.5	431	45	69	
700	371	22.8	157	60	414	40	68	
900	482	20.9	144	56.4	389	37	68	
1100	593	18.8	130	49.3	340	37	68	
1300	704	16.4	113	38	262	48	71	
1500	816	13.4	92	23	159	70	75	
1700	927			12.5	86	60	80	
1900	1038			6.7	46	65	78	
2000	1093			4.0	28	85	80	

REPRESENTATIVE CREEP AND RUPTURE PROPERTIES

Test Temperature		Stress for a Creep Rate of				Stress for Rupture in			
		0.0001% per Hour (1% in 10,000 Hours)		0.00001% per Hour (1% in 100,000 Hours)		1,000 Hours		10,000 Hours	
°F	°C	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
1000	538					54	372	40	176
1100	593	20.3	140	12.4	85	35	241	24.8	171
1200	649	12	83	7	48	22.3	154	15.2	105
1300	704	7.1	49	4	28	13.9	96	9.2	63
1400	760	4.2	29	2.3	16	8.8	61	5.6	39
1500	816	2.5	17	1.3	9	5.5	38	3.4	23

EFFECT OF PROLONGED EXPOSURE AT ELEVATED TEMPERATURES

Representative Mechanical Properties at Room Temperature

10,000 Hours (Without Stress) Exposure Temp.		Yield Strength 0.2% Offset		Tensile Strength		Elongation in 2" (50.80mm)	Reduction of Area
°F	°C	ksi	MPa	ksi	MPa	%	%
900*	482	45.6	314	84.7	584	51	81
1050*	566	32.2	222	86.6	597	48	70
1200	649	25.8	178	82.1	566	48	62

* 100,000 Hours

PHYSICAL PROPERTIES

Thermal Conductivity

	Btu/hr/sq ft/ft/°F	W/m•K
212°F (100°C)—	9.3	0.112
932°F (500°C)—	12.8	0.154

Mean Coefficient of Thermal Expansion per Degree °F (°C) ($\times 10^6$)

32 to 212°F (0 to 100°C)— 9.3 (16.6)
32 to 600°F (0 to 315°C)— 9.5 (17.2)
32 to 1000°F (0 to 538°C)— 10.3 (18.6)
32 to 1200°F (0 to 649°C)— 10.7 (19.3)
32 to 1500°F (0 to 815°C)— 11.2 (20.2)
32 to 1700°F (0 to 926°C)— 11.4 (20.6)

Modulus of Elasticity

Temperature °F	°C	Modulus	psi ($\times 10^6$)	GPa
80	27	Tension	28.0	193
200	93	Tension	28.0	193
		Shear	10.8	74
300	149	Tension	27.3	188
		Shear	10.6	73
400	204	Tension	26.5	183
		Shear	10.3	71
500	260	Tension	25.8	178
		Shear	9.9	68
600	316	Tension	25.3	174
		Shear	9.7	67
700	371	Tension	24.5	169
		Shear	9.4	65
800	427	Tension	23.9	164
		Shear	9.1	63
900	482	Tension	23.2	160
		Shear	8.8	61
1000	538	Tension	22.5	155
		Shear	8.5	59
1100	593	Tension	21.9	151
		Shear	8.2	57
1200	649	Tension	21.2	146
		Shear	7.9	54
1300	704	Tension	20.4	141
		Shear	7.7	53
1400	760	Tension	19.7	136
		Shear	7.4	51
1500	816	Tension	19.1	132
		Shear	7.1	49

TYPE 347 S34700

				CHEMICAL COMPOSITION, **(Maximum unless noted otherwise)**							
C	**Mn**	**P**	**S**	**Si**	**Cr**	**Ni**	**N**	**Mo**	**Ti**	**Al**	**Cb + Ta**
0.08	2.00	0.045	0.030	1.00	17.00/ 19.00	9.00/ 13.00					10XC min.

REPRESENTATIVE MECHANICAL PROPERTIES
(Annealed sheet unless noted otherwise)

Test Temperature		Yield Strength 0.2% Offset		Tensile Strength		Elongation in 2" (50.80mm)	Reduction of Area	Hardness Rockwell
°F	°C	ksi	MPa	ksi	MPa	%	%	B
80	27	40	276	95	655	45		85
300	149	29.6	204	73.9	510	42	76	
500	260	27	186	69	476	35	75	
700	371	25.2	174	67	462	33	71	
900	482	23.6	163	64	441	34	68	
1100	593	22	152	57	393	38	67	
1300	704	20.4	141	40.5	279	49	72	
1500	816	17.6	121	24	165	69	92	
1700	927			14.5	100	22	40	
1900	1038			10	69	18	50	
2000	1093			5	34	63	71	

REPRESENTATIVE CREEP AND RUPTURE PROPERTIES

Test Temperature		Stress for a Creep Rate of				Stress for Rupture in			
		0.0001% per Hour (1% in 10,000 Hours)		0.00001% per Hour (1% in 100,000 Hours)		1,000 Hours		10,000 Hours	
°F	°C	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
1000*	538	53	365	30.5	210	62	427	48	331
1100*	593	27.5	190	16.2	112	36	248	27.5	190
1200*	649	14.8	102	8.7	60	21	145	15.6	108
1300*	704	7.8	54	4.7	32	12.8	88	9	62
1400*	760	4.1	28	2.5	17	7.3	50	5.1	35
1500*	816	2.2	15	1.3	9	4.2	29	2.9	20

*These properties apply to Type 347H. Somewhat lower values may be expected for Type 347 depending upon heat treatment.

EFFECT OF PROLONGED EXPOSURE AT ELEVATED TEMPERATURES

Representative Mechanical Properties at Room Temperature

100,000 Hours (Without Stress) Exposure Temp.		Yield Strength 0.2% Offset		Tensile Strength		Elongation in 2" (50.80mm)	Reduction of Area
°F	°C	ksi	MPa	ksi	MPa	%	%
900	482	35.9	248	90.6	625	52	72
1050	566	36	248	92.3	636	50	66
1200	649	27.2	188	90.5	624	42	52

PHYSICAL PROPERTIES				

Thermal Conductivity

	Btu/hr/sq ft/ft/°F	W/m•K
212°F (100°C)—	9.3	0.112
932°F (500°C)—	12.8	0.154

Mean Coefficient of Thermal Expansion per Degree °F (°C) ($\times 10^6$)

32 to 212°F (0 to 100°C)— 9.3 (16.6)
32 to 600°F (0 to 315°C)— 9.5 (17.2)
32 to 1000°F (0 to 538°C)— 10.3 (18.6)
32 to 1200°F (0 to 649°C)— 10.6 (19.1)
32 to 1500°F (0 to 815°C)— 11.1 (20.0)

Modulus of Elasticity

Temperature		Modulus	psi ($\times 10^6$)	GPa
°F	°C			
80	27	Tension	28.0	193
200	93	Tension	28.2	194
		Shear	11.0	76
300	149	Tension	27.5	190
		Shear	10.7	74
400	204	Tension	26.8	185
		Shear	10.4	72
500	260	Tension	26.1	180
		Shear	10.1	70
600	316	Tension	25.4	175
		Shear	9.8	68
700	371	Tension	24.8	171
		Shear	9.5	66
800	427	Tension	24.1	166
		Shear	9.2	63
900	482	Tension	23.4	161
		Shear	8.9	61
1000	538	Tension	22.8	157
		Shear	8.6	59
1100	593	Tension	22.0	152
		Shear	8.3	57
1200	649	Tension	21.4	148
		Shear	8.1	56
1300	704	Tension	20.7	143
		Shear	7.8	54
1400	760	Tension	20.0	138
		Shear	7.5	52
1500	816	Tension	19.4	134
		Shear	7.2	50
1600	871	Tension	18.7	129
		Shear	6.9	48