CRWMS/M&O

Calculation Cover Sheet

Complete only applicable items.

1. QA: L

Page: 1 Of: 99

2. Calculation Title Waste Package Materials Properties			
3. Document Identifier (including Revision Number) BBA000000-01717-0210-00017 REV 00			4. Total Pages 99
5. Total Attachments 0	6. Attachment Numbers - Number of pages in each		
	Print Name	Signature	Date
7. Originator	Venkataraman Pasupathi	Venkataraman Pasupathi	3/30/99
8. Checker	Bryan J. Harkins	Bryan J. Harkins	26 March 99
9. Lead Design Engineer	David Stahl	David Stahl	4/5/99
10. Remarks			

Revision History

11. Revision No.	12. Date Approved	13. Description of Revision
00		Initial Issue

Title: Waste Package Material Properties

Document Identifier: BBA000000-01717-0210-00017 REV00

Originator: V. Pasupathi

Checker: Bryan J. Harkins

Lead Discipline Engineer: David Stahl

Department Manager: David Stahl

Draft Date: 23 February 1999

Table of Contents

1. Purpose

The objective of this analysis is to compile and identify the appropriate properties of materials that will be used by Waste Package Operations (WPO) as inputs to design analyses, calculations, and technical documents. This report is expected to be a 'ready-reference' for all future work involving such materials. Also, this ensures standardization of data that will be used in the various WPO documents.

2. Method

The Chemical, Thermal, and Mechanical properties for various materials were identified from industry and standard sources and are listed in this report. No designs were analyzed. In the case of contradicting data among different sources, the most appropriate or a possible range is suggested.

3. Assumptions

None

4. Use of Computer Software

None

5. Properties of Materials

Following sections show a compilation of properties for the materials of interest. For many of the material properties, several references are shown as superscripts. The one reference chosen as the source for the specific material properties presented in the report is enclosed within parentheses, and includes page number, table number, etc. The multiple references provide a comprehensive list of the references that were considered for preparation of this report. The purpose of including multiple references is to provide the user with the flexibility in evaluating additional sources and to assure completeness.

All data is considered to be data generally accepted by the scientific and engineering community, and is therefore accepted data.

For mass calculations, utilize the highest density value when a range is given.

5.1 A 516 Carbon Steel Grade 55

(Universal Numbering System (UNS) K01800)

Density[5,9] = 7850 kg/m^3 (Ref. 9, Page 21)

Composition in Weight %[1,10]

(Ref. 1, Page 321, Table 1)

Carbon, max	
½ in. (12.5 mm) and under	0.18
Over ½ in. to 2 in. (12.5-50 mm), incl. [b]	0.20
Over 2 in. to 4 in. (50-100 mm), incl.	0.22
Over 4 to 8 in. (100-200 mm), incl.	0.24
Over 8 in. (200 mm)	0.26
Manganese	
½ in. (12.5 mm) and under:	
Heat analysis	0.60-0.90
Product analysis	0.55-0.98
Over ½ in. (12.5 mm):	
Heat analysis	0.60-1.20
Product analysis	0.55-1.30
Phosphorus, max	0.035
Sulfur, max	0.035
Silicon:	
Heat analysis	0.15-0.40
Product analysis	0.13-0.45
Iron	Balance[a]

[a]Assumption
[b]Inclusive

Mechanical Properties

Poisson's Ratio[3] = 0.28 (room temperature) (Ref. 3, Page 339, Table 6)
Data does not exist for A-516 Carbon Steel; Data for P/M Steels with density, elastic modulus and coefficient of thermal expansion similar to A 516 Grade 55 has been reported.

Tensile Strength[1,3,10] = *379-517 MPa (55-75 ksi) (Ref. 1, Page 321, Table 2)

Yield Strength[1,3,10] = *207 MPa (30 ksi) (Ref. 1, Page 321, Table 2)

Elongation[1,3,10] (in 200 mm) = 23% (min) (Ref. 1, Page 321, Table 2)

Elongation[1,3,10] (in 50 mm) = 27% (min) (Ref. 1, Page 321, Table 2)
Determined by either the 0.2% offset method or the 0.5% extension-under-load method.

(Ref. 7, Page 614, Table TM-1)

Temperature K (°F)	Modulus of Elasticity[7a] GPa (10^6 psi)
*74.82 (-325)	*216.49 (31.4)
*144.26 (-200)	*212.36 (30.8)
*199.82 (-100)	*208.22 (30.2)
*294.26 (70)	*203.39 (29.5)
*366.48 (200)	*198.57 (28.8)
*422.04 (300)	*195.12 (28.3)
*477.59 (400)	*190.98 (27.7)
*533.15 (500)	*188.23 (27.3)
*588.70 (600)	*184.09 (26.7)
*644.26 (700)	*175.82 (25.5)
*699.82 (800)	*166.85 (24.2)
*755.37 (900)	*154.44 (22.4)

[a]Data for Carbon Steels with C< 0.30%

Thermal Properties

(Ref. 8, Page 746, Table A-1)

Temperature K	Specific Heat[8] J/kg·K
300	434
400	487
600	559
800	685

Emissivity[2] = 0.80 (oxidized carbon steel) (Ref. 2, Page 10-298, Spectral Emissivity of Oxides Table)

(Ref. 4, Page 600, Table TCD)

Temperature K (°F)	Thermal Diffusivity[4] 10^{-5} m^2/s (ft^2/h)	Thermal Conductivity[4] W/m·K (Btu/h·ft·°F)
294.26 (70)	*1.171 (0.454)	*40.84 (23.6)
310.93 (100)	*1.143 (0.443)	*41.36 (23.9)
338.70 (150)	*1.117 (0.433)	*41.88 (24.2)
366.48 (200)	*1.089 (0.422)	*42.23 (24.4)
394.26 (250)	*1.068 (0.414)	*42.23 (24.4)
422.04 (300)	*1.048 (0.406)	*42.23 (24.4)
449.82 (350)	*1.022 (0.396)	*42.06 (24.3)
477.59 (400)	*0.996 (0.386)	*41.88 (24.2)
505.37 (450)	*0.968 (0.375)	*41.36 (23.9)
533.15 (500)	*0.939 (0.364)	*41.02 (23.7)
560.93 (550)	*0.916 (0.355)	*40.50 (23.4)
588.70 (600)	*0.893 (0.346)	*39.98 (23.1)
616.48 (650)	*0.859 (0.333)	*39.29 (22.7)
644.26 (700)	*0.826 (0.320)	*38.77 (22.4)
672.04 (750)	*0.795 (0.308)	*38.08 (22.0)
699.82 (800)	*0.769 (0.298)	*37.56 (21.7)
727.59 (850)	*0.738 (0.286)	*36.69 (21.2)
755.37 (900)	*0.707 (0.274)	*36.17 (20.9)
783.15 (950)	*0.676 (0.262)	*35.48 (20.5)
810.93 (1000)	*0.640 (0.248)	*34.61 (20.0)
838.70 (1050)	*0.612 (0.237)	*33.92 (19.6)
866.48 (1100)	*0.588 (0.228)	*33.23 (19.2)
894.26 (1150)	*0.550 (0.213)	*32.36 (18.7)
922.04 (1200)	*0.508 (0.197)	*31.50 (18.2)
949.82 (1250)	*0.462 (0.179)	*30.29 (17.5)
977.59 (1300)	*0.400 (0.155)	*28.90 (16.7)
1005.37 (1350)	*0.307 (0.119)	*27.35 (15.8)
1033.15 (1400)	*0.199 (0.077)	*26.48 (15.3)
1060.93 (1450)	*0.397 (0.154)	*26.13 (15.1)
1088.70 (1500)	*0.436 (0.169)	*26.13 (15.1)

(Ref. 6, Page 588-589, Table TE-1)

Temperature K (°F)	Mean Coefficient of Linear Expansion[6] 10^{-6} m/m·K (μm/m·°F)
*310.93 (100)	*9.95 (5.53)
*338.71 (150)	*10.28 (5.71)
*366.48 (200)	*10.60 (5.89)
*394.26 (250)	*10.96 (6.09)
*422.04 (300)	*11.27 (6.26)
*449.82 (350)	*11.57 (6.43)
*477.59 (400)	*11.90 (6.61)
*505.37 (450)	*12.19 (6.77)
*533.15 (500)	*12.44 (6.91)
*560.93 (550)	*12.71 (7.06)
*588.70 (600)	*12.91 (7.17)
*616.48 (650)	*13.14 (7.30)
*644.26 (700)	*13.34 (7.41)
*672.04 (750)	*13.50 (7.50)
*699.82 (800)	*13.66 (7.59)

*Data converted to SI units[11]

1. American Society for Testing and Materials (ASTM) 1990. *Standard Specification for Pressure Vessel Plates, Carbon Steel, for Moderate and Lower Temperature Service.* ASTM Designation: A516/A516M-90. Philadelphia, PA: ASTM. TIC: 240032
2. Lide, D. R. 1995. *CRC Handbook of Chemistry and Physicis, 76th Edition, 1995-1996.* Boca Raton, FL: CRC Press. TIC: 216194
3. American Society for Metals 1978. *Metals Handbook, Volume 1, 9th Edition, Properties and Selection: Irons and Steels.* Materials Park, OH: American Society for Metals. TIC: 209799
4. American Society of Mechanical Engineers (ASME) 1995. *ASME Boiler and Pressure Vessel Code, ASME Section II-D95, Table TCD, Nominal Coefficients of Thermal Conductivity (TC) and Thermal Diffusivity (TD).* ASME Designation: ASME Section II-D95, Table TCD. New York, NY: ASME. TIC: 239596

5. American Society of Testing and Materials 1995. *Standard Specification for General Requirements for Steel Plates for Pressure Vessels.* ASTM Designation: A20/A20M-95a. Philadelphia, PA: ASTM. TIC: 240026
6. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Codes, Section II, Table TE-1, Nominal Coefficients of Thermal Expansion for Ferrous Materials.* ASME Designation: Section II, Table TE-1. New York, NY: ASME. TIC: 242715
7. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Codes, Section II, Table TM-1, Moduli of Elasticity E of Ferrous Materials for given Temperatures.* ASME Designation: Section II, Table TM-1. New York, NY: ASME. TIC: 242716
8. Incropera, F. P.; DeWitt, D. P. 1985. *Introduction to Heat Transfer, Third Edition.* New York, NY: John Wiley & Sons. TIC: 239934
9. American Society of Mechanical Engineers 1995. *Specification for General Requirements for Steel Plates for Pressure Vessels.* ASME Designation: Section II A SA-20/SA-20M: New York, NY: ASME. TIC: 242374
10. American Society of Mechanical Engineers 1995. *Specifications for Pressure Vessel Plates, Carbon Steel, for Moderate- and Lower-Temperature Service.* ASME Designation: Section II A SA-516/SA-516M: New York, NY: ASME. TIC: 242378
11. American Society of Testing and Materials 1997. *Standard Practice for Use of the International System of Units (SI): The Modern Metric System.* ASTM Designation: ASTM SI 10-1997. West Conshohocken, PA: ASTM. TIC: 240989

5.2 516 Carbon Steel Grade 70
(UNS K02700)

Density[3,5] = 7850 kg/m^3 (Ref. 5, Page 21)

Composition in Weight %[1,6]

(Ref. 1, Page 321, Table 1)

Carbon, max	
½ in. (12.5 mm) and under	0.27
Over ½ in. to 2 in. (12.5-50 mm), incl.	0.28
Over 2 in. to 4 in. (50-100 mm), incl.	0.30
Over 4 to 8 in. (100-200 mm), incl.	0.31
Over 8 in. (200 mm)	0.31
Manganese	
½ in. (12.5 mm) and under:	
Heat analysis	0.85-1.20
Product analysis	0.79-1.30
Over ½ in. (12.5 mm):	
Heat analysis	0.85-1.20
Product analysis	0.79-1.30
Phosphorus, max	0.035
Sulfur, max	0.035
Silicon:	
Heat analysis	0.15-0.40
Product analysis	0.13-0.45
Iron	Balance[a]

[a]Assumption

Mechanical Properties

Poisson's Ratio[9] = 0.28 (room temperature) (Ref. 2, Page 339, Table 6)

Tensile Strength[1,2,6] = *483-620 MPa (70-90 ksi) (Ref. 1, Page 321, Table 2)

Yield Strength[1,2,6] = *262 MPa (38 ksi) (Ref. 1, Page 321, Table 2)

Elongation[1,2,6] (in 200 mm) = 17% (min) (Ref. 1, Page 321, Table 2)

Elongation[1,2,6] (in 50 mm) = 21% (min) (Ref. 1, Page 321, Table 2)
Determined by either the 0.2% offset method or the 0.5% extension-under-load method.

(Ref. 4, Page 614, Table TM-1)

Temperature K (°F)	Modulus of Elasticity[4] GPa (10^6 psi)
*74.82 (-325)	*215.12 (31.2)
*144.26 (-200)	*210.98 (30.6)
*199.82 (-100)	*206.84 (30.0)
*294.26 (70)	*202.02 (29.3)
*366.48 (200)	*197.19 (28.6)
*422.04 (300)	*193.74 (28.1)
*477.60 (400)	*189.60 (27.5)
*533.15 (500)	*186.85 (27.1)
*588.70 (600)	*182.71 (26.5)
*644.26 (700)	*174.44 (25.3)
*699.82 (800)	*165.47 (24.0)
*755.37 (900)	*153.75 (22.3)

Assumption: The above values should be used only when C>0.3%, in case of C≤0.3% refer to values listed in A 516 Grade 55.

Other Properties:
Similar to A 516 Grade 55

*Data converted to SI units[7]

1. American Society for Testing and Materials 1990. *Standard Specification for Pressure Vessel Plates, Carbon Steel, for Moderate and Lower Temperature Service.* ASTM Designation: A516/A516M-90. Philadelphia, PA: ASTM. TIC: 240032
2. American Society for Metals 1978. *Metals Handbook, Volume 1, 9th Edition, Properties and Selection: Irons and Steels.* Materials Park, OH: American Society for Metals. TIC: 209799
3. American Society of Testing and Materials 1995. *Standard Specification for General Requirements for Steel Plates for Pressure Vessels.* ASTM Designation: A20/A20M-95a. Philadelphia, PA: ASTM. TIC: 240026.
4. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Codes, Section II, Table TM-1, Moduli of Elasticity E of Ferrous Materials for given Temperatures.* ASME Designation: Section II, Table, TM-1. New York, NY: ASME. TIC: 242716

5. American Society of Mechanical Engineers 1995. *Specification for General Requirements for Steel Plates for Pressure Vessels*. ASME Designation: Section II A SA-20/SA-20M: New York, NY: ASME. TIC: 242374
6. American Society of Mechanical Engineers 1995. *Specifications for Pressure Vessel Plates. Carbon Steel, for Moderate- and Lower-Temperature Service*. ASME Designation: Section II A SA-516/SA-516M: New York, NY: ASME. TIC: 242378
7. American Society of Testing and Materials 1997. *Standard Practice for Use of the International System of Units (SI): The Modern Metric System*. ASTM Designation: ASTM SI 10-1997. West Conshohocken, PA: ASTM. TIC: 240989

5.3 Stainless Steel 316L
(UNS S31603)

Density[8] = 7980 kg/m^3 (Ref. 8, Page 7, Table X1)

Composition in Weight %[5]

(Ref. 5, Page 2, Table 1)

C	0.03 (max)
Mn	2.00 (max)
P	0.045 (max)
S	0.03 (max)
Si	1.00 (max)
Cr	16.00-18.00
Ni	10.00-14.00
Mo	2.00-3.00
N	0.10 (max)
Fe	Balance[a]

[a]Assumption

Mechanical Properties

(Ref. 5, Page 4, Table 2)

Condition	Ultimate Tensile Strength[5] MPa (ksi)	0.2% Yield Strength[5] MPa (ksi)	Elongation[5], %
Hot finished and annealed	*483 (70)	*172 (25)	40
Cold finished and annealed	*620 (90)	*310 (45)	30
Cold finished and annealed	*483 (70)	*172 (25)	30

Poisson's Ratio[7] = 0.299 (room temperature) (Ref. 7, Page 755, Figure 15)

Modulus of Elasticity[1] = 28 x 10^6 psi *(193 GPa) (Ref. 1, Page 34, Table 12)

Emissivity = 0.28 (Ref. 3, Page 4-68, Table 4.3.2)

Thermal Properties

(Ref. 6, Page 747, Table A-1)

Temperature K	Specific Heat[6] J/kg·K
300	468
400	504
600	550
800	576
1000	602

(Ref. 4, Page 606, Table TCD)

Temperature K (°F)	Thermal Conductivity[4] W/m·K (Btu/h·ft·°F)
*294.26 (70)	*13.33 (7.7)
*310.93 (100)	*13.67 (7.9)
*338.70 (150)	*14.19 (8.2)
*366.48 (200)	*14.54 (8.4)
*394.26 (250)	*15.06 (8.7)
*422.04 (300)	*15.58 (9.0)
*449.82 (350)	*15.92 (9.2)
*477.59 (400)	*16.44 (9.5)
*505.37 (450)	*16.96 (9.8)
*533.15 (500)	*17.31 (10.0)
*560.93 (550)	*17.83 (10.3)
*588.70 (600)	*18.17 (10.5)
*616.48 (650)	*18.52 (10.7)
*644.26 (700)	*19.04 (11.0)
*672.04 (750)	*19.38 (11.2)
*699.82 (800)	*19.90 (11.5)
*727.59 (850)	*20.25 (11.7)
*755.37 (900)	*20.77 (12.0)
*783.15 (950)	*21.11 (12.2)
*810.93 (1000)	*21.46 (12.4)
*838.70 (1050)	*21.98 (12.7)
*866.48 (1100)	*22.33 (12.9)
*894.26 (1150)	*22.67 (13.1)
*922.04 (1200)	*23.02 (13.3)
*949.82 (1250)	*23.54 (13.6)
*977.59 (1300)	*23.88 (13.8)
*1005.37 (1350)	*24.23 (14.0)
*1033.15 (1400)	*24.58 (14.2)
*1060.93 (1450)	*24.92 (14.4)
*1088.70 (1500)	*25.27 (14.6)

(Ref. 2, Page 2, Coefficient of Expansion Table)

Temperature Range K (°C)	Coefficient of Linear Expansion[2] 10^{-6} m/m·K (cm/cm·°C x 10^{-6})
293-373 (20-100)	*16.5 (16.5)
293-773 (20-500)	*18.2 (18.2)
293-1273 (20-1000)	*19.5 (19.5)

*Data converted to SI units[8]

1. American Society for Metals 1980. *Metals Handbook, 9th Edition; Properties and Selection: Stainless Steels, Tool Materials and Special-Purpose Metals.* Metals Park, OH: American Society for Metals. TIC: 209801
2. Allegheny Ludlum Corporation 1987. *Technical Data Blue Sheet Stainless Steels Chromium-Nickel-Molybdenum Types 316, 316L, 317 and 317L.* Pittsburg, PA: Allegheny Ludlum Corporation. TIC: 240370
3. Avallone, E. A.; Baumeister, T. 1987. *Mark's Standard Handbook for Mechanical Engineers, 9th Edition.* New York, NY: McGraw-Hill Book Company. TIC: 239873
4. American Society of Mechanical Engineers 1995. *ASME Boiler and Pressure Vessel Codes, Section II, Table TCD, Nominal Coefficients of Thermal Conductivity and Thermal Diffusivity.* ASME Section II, Table TCD. New York, NY: American Society of Mechanical Engineers. TIC: 239596
5. American Society for Testing and Materials 1991. *Standard Specification for Stainless and Heat-Resisting Steel Bars and Shapes.* ASME Designation: ASTM A 276-91a. Philadelphia, PA: ASTM. TIC: 240022
6. Incropera, F. P.; DeWitt, D. P. 1985. *Introduction to Heat Transfer, 3rd Edition.* New York, NY: John Wiley & Sons. TIC: 239934
7. American Society of Testing and Materials 1994. *Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens.* ASTM Designation: ASTM G1-90. Philadelphia, PA: ASTM. TIC: 238771
8. American Society of Testing and Materials 1997. *Standard Practice for Use of the International System of Units (SI): The Modern Metric System.* ASTM Designation: ASTM SI 10-1997. West Conshohocken, PA: ASTM. TIC: 240989

5.4 Stainless Steel 304L
(UNS S30403, 18-8 Stainless Steel)

Density[1] = 7940 kg/m^3 (Ref. 1, Page 7, Table X1)

Composition in Weight %[5,6]

(Ref. 5, Page 2, Table 1)

C	0.03 (max)
Mn	2.0 (max)
P	0.045 (max)
S	0.03 (max)
Si	0.75 (max)
Cr	18-20
Ni	8-12
N	0.10
Fe	Balance[a]

[a]Assumption

Mechanical Properties

(Ref. 2, Page 6, Low & Elevated Temperature Properties Table)

Temperature K (°F)	Tensile Strength[2] MPa (ksi)	0.2% Yield Strength[2] MPa (ksi)	Elongation[2], (%) in 2 in.
20.15 (-423)	1725 (250)	690 (100)	25
77.15(-320)	1585 (230)	485 (70)	35
352.15 (-100)	1035 (150)	345 (50)	50
294.15 (70)	620 (90)	240 (35)	60
478.15 (400)	485 (70)	160 (23)	50
700.15 (800)	455 (66)	130 (19)	43
923.15 (1200)	330 (48)	105 (15.5)	34
1088.15 (1500)	160 (23)	90 (13)	46

Modulus of Elasticity[2] = 28 x 10^6 psi (193 GPa) (Ref. 2, Page 4, Figure 15)

Poisson's Ratio[7] = 0.29 (Ref. 7, Page 755)

Thermal Properties

Specific Heat[2] *(273.15-373.15 K) = 500 J/kg·K (Ref. 2, Page 4)

Thermal Conductivity[2] *(293.15-373.15 K) = 16.3 W/m·K (Ref. 2, Page 4)
*(293.15-773.15 K) = 21.4 W/m·K

Emissivity[3] *(493.15-803.15 K) = 0.62-0.73 (Ref. 3, Page 4-68, Table 4.3.2)
Data not available for SS 304L. Values for SS 304 have been used instead.

(Ref. 6, Table TCD, Page 606)

Temperature K (°F)	Thermal Conductivity[4,6] W/m·K (Btu/h·ft·°F)
*294.26 (70)	*14.88 (8.6)
*310.93 (100)	*15.06 (8.7)
*338.70 (150)	*15.58 (9.0)
*366.48 (200)	*16.09 (9.3)
*394.26 (250)	*16.61 (9.6)
*422.04 (300)	*16.96 (9.8)
*449.82 (350)	*17.48 (10.1)
*477.59 (400)	*18.00 (10.4)
*505.37 (450)	*18.34 (10.6)
*533.15 (500)	*18.86 (10.9)
*560.93 (550)	*19.21 (11.1)
*588.70 (600)	*19.56 (11.3)
*616.48 (650)	*20.08 (11.6)
*644.26 (700)	*20.42 (11.8)
*672.04 (750)	*20.77 (12.0)
*699.82 (800)	*21.11 (12.2)
*727.59 (850)	*21.63 (12.5)
*755.37 (900)	*21.98 (12.7)
*783.15 (950)	*22.33 (12.9)
*810.93 (1000)	*22.84 (13.2)
*838.70 (1050)	*23.18 (13.4)
*866.48 (1100)	*23.53 (13.6)
*894.26 (1150)	*23.87 (13.8)
*922.04 (1200)	*24.22 (14.0)
*949.82 (1250)	*24.74 (14.3)
*977.59 (1300)	*25.09 (14.5)
*1005.37 (1350)	*25.44 (14.7)
*1033.15 (1400)	*25.79 (14.9)
*1060.93 (1450)	*26.13 (15.1)
*1088.70 (1500)	*26.48 (15.3)

*Data converted to SI units[8]

1. American Society of Testing and Materials 1994. *Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens.* ASTM Designation: ASTM G1-90. Philadelphia, PA: ASTM. TIC: 238771
2. Allegheny Ludlum Corporation 1987. *Steel, Technical Data Blue Sheet Allegheny Ludlum Stainless Steel Types 302 (530200), 304 (530400), 304L (530403), 305 (530500).* Pittsburg, PA: Allegheny Ludlum Corporation. TIC: 240372
3. Avallone, E. A.; Baumeister, T. 1987. *Mark's Standard Handbook for Mechanical Engineers, 9th Edition.* New York, NY: McGraw-Hill Book Company. TIC: 239873
4. American Society for Mechanical Engineers 1995. *Boiler and Pressure Vessel Codes, Section II, Table TM-1, Nominal Coefficients of Thermal Conductivity and Thermal Diffusivity.* ASME Designation: ASME Section II, Table TCD. New York, NY: ASME. TIC: 239596
5. American Society for Testing and Materials 1995. *Standard Specification for Heat-Resisting Chromium-Nickel Stainless Steel Plate, Sheet, and Strip for Pressure Vessels.* ASTM Designation: ASTM A 240/A 240M-94b. Philadelphia, PA: ASTM. TIC: 240020
6. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Codes, Section II A SM-240 Specification for Heat-Resisting Chromium and Chromium-Nickel Stainless Steel.* ASME Designation: ASME Section II, SA-240. New York, NY: ASME. TIC: 239714
7. American Society for Metals 1980. *Metals Handbook, 9th Edition, Properties and Selection: Stainless Steels, Tool Materials and Special-Purpose Metals.* Materials Park, OH: American Society for Metals. TIC: 209801
8. American Society of Testing and Materials 1997. *Standard Practice for Use of the International System of Units (SI): The Modern Metric System.* ASTM Designation: ASTM SI 10-1997. West Conshohocken, PA: ASTM. TIC: 240989

5.5 Stainless Steel 304

(UNS S30400, 18-8 Stainless Steel)

Density[8] = 7940 kg/m^3 (Ref. 8, Page 7, Table X1)

Composition in Weight %[3,4,9]

(Ref. 3, Page 2, Table 1)

C	0.08 (max)
Cr	18-20
Ni	8-10.5
Mn	2.00 (max)
P	0.045 (max)
S	0.03 (max)
Si	1.00 (max)
N	0.10 (max)
Fe	Balance[a]

[a]Assumption

Thermal Properties

(Ref. 1, Page 273)

Temperature K (°C)	Average Coefficients of Linear Thermal Expansion[1,4] 10^{-6} m/m·K
273.15-373.15 (0-100)	17.3
273.15-588.15 (0-315)	17.8
273.15-813.15 (0-540)	18.4
273.15-923.15 (0-650)	18.7

(Ref. 1, Page 273)

Temperature K	Specific Heat 10^3 J/kg·K
100	0.272
200	0.402
300	0.477
400	0.515
600	0.557
800	0.582
1000	0.611
1200	0.640
1500	0.682

(Ref. 7, Page 606, Table TCD)

Temperature K (°F)	Thermal Conductivity[7,2] W/m·K (Btu/h·ft·°F)
*294.26 (70)	*14.88 (8.6)
*310.93 (100)	*15.06 (8.7)
*338.70 (150)	*15.58 (9.0)
*366.48 (200)	*16.09 (9.3)
*394.26 (250)	*16.61 (9.6)
*422.04 (300)	*16.96 (9.8)
*449.82 (350)	*17.48 (10.1)
*477.59 (400)	*18.00 (10.4)
*505.37 (450)	*18.34 (10.6)
*533.15 (500)	*18.86 (10.9)
*560.93 (550)	*19.21 (11.1)
*588.70 (600)	*19.56 (11.3)
*616.48 (650)	*20.08 (11.6)
*644.26 (700)	*20.42 (11.8)
*672.04 (750)	*20.77 (12.0)
*699.82 (800)	*21.11 (12.2)
*727.59 (850)	*21.63 (12.5)
*755.37 (900)	*21.98 (12.7)
*783.15 (950)	*22.33 (12.9)
*810.93 (1000)	*22.84 (13.2)
*838.70 (1050)	*23.19 (13.4)
*866.48 (1100)	*23.54 (13.6)
*894.26 (1150)	*23.88 (13.8)
*922.04 (1200)	*24.23 (14.0)
*949.82 (1250)	*24.75 (14.3)
*977.59 (1300)	*25.09 (14.5)
*1005.37 (1350)	*25.44 (14.7)
*1033.15 (1400)	*25.79 (14.9)
*1060.93 (1450)	*26.13 (15.1)
*1088.70 (1500)	*26.48 (15.3)

Mechanical Properties

(Ref. 1, Page 274)

Temperature K (°C)	Tensile Strength MPa	Yield Strength MPa	Elongation, % in 2 in. or 50 mm
78.15 (-195)	1620	386	40
211.15 (-62)	1110	345	57
233.15 (-40)	1000	385	60
273.15 (0)	840	345	65
294.15 (21)	585	330	57
478.15 (205)	495	275	51
588.15 (315)	470	255	45
698.15 (425)	440	160	40
813.15 (540)	385	135	36
923.15 (650)	305	115	34
1033.15 (760)	200	76	36
1143.15 (870)	110	-	40

Modulus of Elasticity[1] (tension) = 193 GPa (Ref. 1, Page 274)
(torsion) = 77 Gpa

Poisson's Ratio[5]= 0.29 (Ref. 5, Page 755, Figure 1.5)

Emissivity[6] (493.15-803.15 K) = 0.62-0.73 (Ref. 6, Page 4-68, Table 4.3.2)

*Data converted to SI units[10]

1. American Society for Metals 1982. *Engineering Properties of Steel.* Materials Park, OH: American Society of Metals. TIC: 239830
2. Incropera, F. P.; DeWitt, D. P. 1985. *Introduction to Heat Transfer, 3rd Edition.* New York, NY: John Wiley & Sons. TIC: 239934
3. American Society for Testing and Materials 1995. *Standard Specification for Heat-Resisting Chromium-Nickel Stainless Steel Plate, Sheet, and Strip for Pressure Vessels.* ASTM Designation: ASTM A 240/A 240M-94b. Philadelphia, PA: ASTM. TIC: 240020
4. Specialty Steel Industry of North America. *Design Guidelines for the Selection and Use of Stainless Steel, Designer Handbook.* Specialty Steel Industry of North America. TIC: 240560

5. American Society for Metals 1978. *Metals Handbook, 9th Edition, Properties and Selection: Irons and Steels.* Materials Park, OH: America Society for Metals. TIC: 209799
6. Avallone, E. A.; Baumeister, T. 1987. *Mark's Standard Handbook for Mechanical Engineers, 9th Edition.* New York, NY: McGraw-Hill Book Company. TIC: 239873
7. American Society of Mechanical Engineers 1995. *ASME Boiler and Pressure Vessel Codes, Section II, Table TCD, Nominal Coefficients of Thermal Conductivity and Thermal Diffusivity.* ASME Section II, Table TCD. New York, NY: ASME. TIC: 239596
8. American Society of Testing and Materials 1994. *Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens.* ASTM Designation: ASTM G1-90. Philadelphia, PA: ASTM. TIC: 238771
9. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Codes, Section II A SM-240 Specification for Heat-Resisting Chromium and Chromium-Nickel Stainless Steel.* ASME Designation: ASME Section II, SA-240. New York, NY: ASME. TIC: 239714
10. American Society of Testing and Materials 1997. *Standard Practice for Use of the International System of Units (SI): The Modern Metric System.* ASTM Designation: ASTM SI 10-1997. West Conshohocken, PA: ASTM. TIC: 240989

5.6 Alloy 625

(INCONEL® Alloy 625, UNS N06625, Altemp® 625 Alloy, HAYNES® 625 Alloy)

Density = 8140[10]-8440[2,3,4] kg/m^3 (Ref. 10, Page 7, Table X 1) - (Ref. 2, Page 2, Table 2)

Composition in Weight %[1,2,7]

(Ref. 1, Page 282, Table 2)

C	0.1 (max)
Mn	0.5 (max)
Si	0.5 (max)
P	0.015 (max)
S	0.015 (max)
Cr	20-23
Nb + Ta	3.15-4.15
Co	1 (max)
Mo	8-10
Fe	5 (max)
Al	0.4 (max)
Ti	0.4 (max)
Ni	58 (min)

Mechanical Properties

Cold-rolled and 1925 °F (1050 °C) mill annealed sheet

(Ref. 3, Page 4)

Temperature K (°F)	Ultimate Tensile Strength[3] ksi (MPa)	Yield Strength[3], at 0.2 % Offset, ksi (MPa)	Elongation[3], in 2 in. (50.8 mm), %
Room[2,3]	131.1 (905)	71.1 (490)	48.5
813.15 (1000)	111.6 (770)	53.7 (370)	54.0
923.15 (1200)	110.1 (760)	53.7 (370)	55.6
1033.15 (1400)	87.2 (600)	50.2 (345)	53.1
1143.15 (1600)	50.0 (345)	29.7 (205)	45.9
1253.15 (1800)	24.1 (165)	12.1 (83)	43.8
1368.15 (2000)	13.7 (95)	5.6 (39)	44.7

(Ref. 5, Page 617, Table TM-4)

Temperature K (°F)	Modulus of Elasticity[5] GPa (x 10^6 psi)
*74.82 (-325)	*221 (32.1)
*144.26 (-200)	*217 (31.5)
*199.82 (-100)	*213 (30.9)
*294.26 (70)	*206.8 (30.0)
*366.48 (200)	*202.0 (29.3)
*422.04 (300)	*198.6 (28.8)
*477.59 (400)	*196.5 (28.5)
*533.15 (500)	*193.7 (28.1)
*588.70 (600)	*191.7 (27.8)
*644.26 (700)	*188.2 (27.3)
*699.82 (800)	*184.1 (26.7)
*755.37 (900)	*179.9 (26.1)
*810.93 (1000)	*175.8 (25.5)

(Ref. 2, Page 2, Table 4)

Temperature K (°F)	Poisson's Ratio[2]	
	Annealed	Solution Treated
*294.26 (70)	0.278	0.312
*366.48 (200)	0.280	0.311
*477.59 (400)	0.286	0.303
*588.70 (600)	0.290	0.300
*699.82 (800)	0.295	0.302
*810.93 (1000)	0.305	0.312
*922.04 (1200)	0.321	0.314
*1033.15 (1400)	0.340	0.305
*1144.26 (1600)	0.336	0.289

Thermal Properties

(Ref. 6, Page 609, Table TCD)

Temperature K (°F)	Thermal Conductivity[6] W/m·K (Btu/h·ft·°F)
*294.26 (70)	*9.86 (5.7)
*310.93 (100)	*10.04 (5.8)
*338.70 (150)	*10.38 (6.0)
*366.48 (200)	*10.73 (6.2)
*394.26 (250)	*11.25 (6.5)
*422.04 (300)	*11.77 (6.8)
*449.82 (350)	*12.11 (7.0)
*477.59 (400)	*12.46 (7.2)
*505.37 (450)	*12.98 (7.5)
*533.15 (500)	*13.33 (7.7)
*560.93 (550)	*13.67 (7.9)
*588.70 (600)	*14.19 (8.2)
*616.48 (650)	*14.54 (8.4)
*644.26 (700)	*14.88 (8.6)
*672.04 (750)	*15.40 (8.9)
*699.82 (800)	*15.75 (9.1)
*727.59 (850)	*16.27 (9.4)
*755.37 (900)	*16.61 (9.6)
*783.15 (950)	*16.96 (9.8)
*810.93 (1000)	*17.48 (10.1)
*838.70 (1050)	*17.83 (10.3)
*866.48 (1100)	*18.34 (10.6)
*894.26 (1150)	*18.69 (10.8)
*922.04 (1200)	*19.04 (11.0)
*949.82 (1250)	*19.56 (11.3)
*977.59 (1300)	*19.90 (11.5)
*1005.37 (1350)	*20.42 (11.8)
*1033.15 (1400)	*20.77 (12.0)
*1060.93 (1450)	*21.29 (12.3)
*1088.70 (1500)	*21.81 (12.6)

(Ref. 3, Page 8, Typical Physical Properties Table)

Temperature K (°C)	Specific Heat[3] J/kg·K
Room	410
*373.15 (100)	428
*473.15 (200)	455
*573.15 (300)	477
*673.15 (400)	503
*773.15 (500)	527
*873.15 (600)	552
*973.15 (700)	576
*1073.15 (800)	600
*1173.15 (900)	625
*1273.15 (1000)	648

(Ref. 8, Page 596, Table TE-4)

Temperature K (°F)	Mean Coefficient of Thermal Expansion[8] 10^{-6}/K (10^{-6}/ °F)
*310.93 (100)	*12.06 (6.70)
*338.70 (150)	*12.51 (6.95)
*366.48 (200)	*12.82 (7.12)
*394.26 (250)	*12.89 (7.16)
*422.04 (300)	*12.96 (7.20)
*449.82 (350)	*13.05 (7.25)
*477.59 (400)	*13.14 (7.30)
*505.37 (450)	*13.18 (7.32)
*533.15 (500)	*13.23 (7.35)
*560.93 (550)	*13.32 (7.40)
*588.70 (600)	*13.41 (7.45)
*616.48 (650)	*13.50 (7.50)
*644.26 (700)	*13.54 (7.52)
*672.04 (750)	*13.61 (7.56)
*699.82 (800)	*13.68 (7.60)

(Ref. 9, Page .002, Table 5)

Temperature K (°C)	Emissivity[9]
*753.15 (480)	0.85
*923.15 (650)	0.87
*1088.15 (815)	0.90
*1253.15 (980)	0.95
*1363.15 (1090)	0.98

Data for Alloy 600 from Inco Alloys International. Similar values (0.87 for 100-600 °C) are also reported for 80Ni-20Cr alloy in Reference 4. No data available for Alloy 625.

*Data converted to SI units[11]

1. American Society for Testing and Materials 1993. *Standard Specification for Nickel-Chromium-Molybdenum-Columbium Alloy (UNSN06625) Plate, Sheet, and Strip.* ASTM Designation: ASTM B 443-93. Philadelphia, PA: ASTM. TIC: 239758
2. Inco Alloys International 1988. *Inco Alloys International Literature on INCONEL Alloy 625.* Huntington, WV: Inco Alloys International, Inc. TIC: 239842
3. Haynes International 1993. *Haynes 625 alloy, A Ni-Cr-Mg-Cb Alloy with Excellent Strength to 1500°F (816°C), Good Oxidation Resistance, and Good Resistance to Aqueous Corrosion.* Kikomo, IN: Haynes International, Inc. TIC: 239935
4. Allegheny Ludlum Steel Corporation 1986. *Technical Data Blue Sheet Allegheny Ludlum Alloy 625 Nickel-Base Super Alloy (UNS Designation: N06625).* Pittsburgh, PA: Allegheny Ludlum Steel. TIC: 240374
5. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Codes, Section II, Table TM-4, Moduli of Elasticity E of High Nickel Alloys for Given Temperatures.* ASME Designation: ASME Section II, Table TM-4. New York, NY: ASME. TIC: 242717
6. American Society of Mechanical Engineers 1995. *ASME Boiler and Pressure Vessel Codes, Section II, Table TCD, Nominal Coefficients of Thermal Conductivity and Thermal Diffusivity.* ASME Section II, Table TCD. New York, NY: ASME. TIC: 239596
7. American Society of Mechanical Engineers 1995. *Boiler and Pressure vessel Code, Section II, B SB-443, Specification for Nickel-Chromium-Molybdenum-Columbium Alloy.* ASME Designation: ASME Section II B SB-443. New York, NY: ASME. TIC: 239704

8. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Codes, Section II, Table TE-4, Nominal Coefficients of Thermal Expansion for High Nickel Alloys*. ASME Designation: ASME Section II, Table TE-4. New York, NY: ASME. TIC: 239681
9. Inco Alloys International 1988. *Inco Alloys International Literature on Inconel Alloy 600*. Huntington, WV: Inco Alloys International, Inc. TIC: 239841
10. American Society of Testing and Materials 1994. *Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens*. ASTM Designation: ASTM G1-90. Philadelphia, PA: ASTM. TIC: 238771
11. American Society of Testing and Materials 1997. *Standard Practice for Use of the International System of Units (SI): The Modern Metric System*. ASTM Designation: ASTM SI 10-197. West Conshohocken, PA: ASTM. TIC: 240989

5.7 Alloy C-22

(HASTELLOY® Alloy C-22, UNS N06022)

Density[1,3,4,5] = 8690 kg/m^3 at 24 °C (Ref. 1, Page 3)

Composition in Weight %[1,5]

(Ref. 1, Page 678, Table 1)

C	0.015 (max)
Mn	0.50 (max)
Si	0.08 (max)
Cr	20.0-22.5
Mo	12.5-14.5
Co	2.50 (max)
W	2.5-3.5
V	0.35 (max)
Fe	2.0-6.0
P	0.02 (max)
S	0.020 (max)
Ni	Remainder

Thermal Properties

(Ref. 3, Page 13)

Temperature K (°F)	Mean Coefficient of Thermal Expansion[3] 10^{-6} m/m·K
*297.04-366.48 (75-200)	12.4
*297.04-477.59 (75-400)	12.4
*297.04-588.70 (75-600)	12.6
*297.04-699.82 (75-800)	13.3
*297.04-810.93 (75-1000)	13.9
*297.04-922.04 (75-1200)	14.6
*297.04-1033.15 (75-1400)	15.3
*297.04-1144.26 (75-1600)	15.8
*297.04-1255.37 (75-1800)	16.2

(Ref. 3, Page 13)

Temperature K (°F)	Thermal Conductivity[3] W/m·K
*320.93 (118)	10.1
*373.15 (212)	11.1
*473.15 (392)	13.4
*573.15 (572)	15.5
*673.15 (752)	17.5
*773.15 (932)	19.5
*873.15 (1112)	21.3

(Ref. 3, Page 13)

Temperature K (°F)	Specific Heat[2,3] J/kg·K
*325.37 (126)	414
*373.15 (212)	423
*473.15 (392)	444
*573.15 (572)	460
*673.15 (752)	476
*773.15 (932)	485
*873.15 (1112)	514

(Ref. 2, Page .002)

Temperature K (°C)	Emissivity[2d]
*753.15 (480)	0.85
*923.15 (650)	0.87
*1088.15 (815)	0.90
*1253.15 (980)	0.95
*1363.15 (1090)	0.98

Data for Alloy 600 from Inco Alloys Inc[4]. Similar values (0.87 for 100-600 °C) are also reported for 80Ni-20Cr alloy in Reference 6. No data available for Alloy C-22.

Mechanical Properties

Poisson's Ratio[7] = 0.278 (Ref. 7, Page 2, Table 4)
Since composition of C-22 is very similar to Alloy 625, Poisson's Ratio for Alloy 625 has been used.

Heat-treated at 2050 °F and rapid quenched

(Ref. 3, Page 14)

Temperature K (°C)	Modulus of Elasticity[3] GPa
Room	206
*366 (93)	203
*477 (204)	196
*589 (316)	190
*700 (427)	183
*811 (538)	177
*922 (649)	171
*1033 (760)	163
*1144 (871)	154
*1255 (982)	145

Sheet, 0.028-0.125 in. (0.713-3.2 mm) thick[3,4]

(Ref. 4, Page 2, Table 3)

Temperature K (°F)	Ultimate Tensile Strength, ksi (MPa)	Yield Strength, at 0.2%, ksi (MPa)	Elongation, in 2 in., %
Room	116.3 (802)	58.5 (403)	57
*366 (200)	109.5(755)	53.8 (371)	58
*477 (400)	101.6 (701)	43.9 (303)	57
*589 (600)	97.7 (674)	41.8 (288)	62
*700 (800)	95.4 (658)	41.0 (283)	67
*811 (1000)	90.7 (625)	39.7 (274)	61
*922 (1200)	84.6 (583)	36.1 (249)	65
*1033 (1400)	76.0 (524)	34.5 (238)	63

Plate, ¼ - ¾ in. (6.4-19.1 mm) thick[3]

(Ref. 3, Page 15)

Temperature K (°F)	Ultimate Tensile Strength, ksi (MPa)	Yield Strength, at 0.2%, ksi (MPa)	Elongation, in 2 in., %
Room	114 (786) *	54 (372) *	62
*366 (200)	107 (738) *	49 (338) *	65
*477 (400)	98 (676) *	41 (283) *	66
*589 (600)	95 (655) *	36 (248) *	68
*700 (800)	92 (634) *	35 (241) *	68
*811 (1000)	88 (607) *	34 (234) *	67
*922 (1200)	83 (572) *	32 (221) *	69
*1033 (1400)	76 (524) *	31(214) *	68

Bar, ½ - 2 in. (12.7 –50.8 mm) diameter[3]

(Ref. 3, Page 15)

Temperature K (°F)	Ultimate Tensile Strength, ksi (MPa)	Yield Strength, at 0.2%, ksi (MPa)	Elongation, in 2 in., %
Room	111 *(765)	52 *(358)	70
*366 (200)	105 *(724)	45 *(310)	73
*477 (400)	96 *(662)	38 *(262)	74
*589 (600)	92 *(634)	34 *(234)	79
*700 (800)	89 *(614)	31 *(214)	79
*811 (1000)	84 *(579)	29 *(200)	80
*922 (1200)	80 *(551)	28 *(193)	80
*1033 (1400)	72 *(496)	29 *(200)	77

*Data converted to SI units[8]

1. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Code, Section II SB-575, Specification for Low-Carbon Nickel-Molybdenum-Chromium, Low-Carbon Nickel-Chromium-Molybdenum, and Low-Carbon Nickel-Chromium-Molybdenum-Tungsten Alloy Plate, Sheet, and Strip.* ASME Designation: ASME Section II, B SB-575. New York, NY: ASME. TIC: 239753
2. Inco Alloys International 1988. *Inco Alloys International Literature on Inconel Alloy 600.* Huntington, WV: Inco Alloys International, Inc. TIC: 239841

3. Haynes International 1988. *Hastelloy Alloy C-22*. Kokomo, IN: Haynes International, Inc. TIC: 239938
4. Alloy Digest 1985. *Hastelloy Alloy C-22. Nickel Chromium-Molybdenum Alloy.* Orange, NJ: Alloy Digest, Inc. TIC: 239931
5. American Society of Testing and Materials 1994. *Standard Specification for Low-Carbon Nickel-Molybdenum-Chromium, Low-Carbon Nickel-Chromium-Molybdenum, and Low-Carbon Nickel-Chromium-Molybdenum-Tungsten Alloy Plate, Sheet, and Strip*. ASTM Designation: ASTM B 575-94. Philadelphia, PA: ASTM. TIC: 239768
6. Lide, D. R. 1995. *CRC Handbook of Chemistry and Physics, 76th Edition, 1995-1996.* Boca Raton, FL: CRC Press. TIC: 216194
7. Inco Alloys International 1988. *Inco Alloys International Literature on Inconel Alloy 625*. Huntington, WV. Inco Alloys International, Inc. TIC: 239842
8. American Society of Testing and Materials 1997. *Standard Practice for Use of the International System of Units (SI): The Modern Metric System*. ASTM Designation: ASTM SI 10-1997. West Conshohocken, PA: ASTM. TIC: 240989

5.8 Alloy 400
(Monel 400, AL 400 alloy, UNS N04400)

Density[1,2,8] = 8830 - 8840 kg/m^3 (Ref. 1, Page 2) - (Ref. 8, Page 7, Table X1)

Composition in Weight %[2,4,7]

(Ref. 2, Page 3, Table 1)

Ni	63 (min)
Cu	28-34
Fe	2.5 (max)
Mn	2.0 (max)
C	0.3 (max)
Si	0.5 (max)
S	0.024 (max)

Thermal Properties

Emissivity[3] (200-600 °C) = 0.43 (oxidized) (Ref. 3, Page 10-297, Emissivity Table)

(Ref. 2, Page 4, Table 3)

Temperature K (°F)	Mean Coefficient of Thermal Expansion 10^{-6}/K (µin/in·°F)	Specific Heat J/kg·K (Btu/lb·°F)
*77.59 (-320)	-	-
*88.70 (-300)	*10.98 (6.1)	*209.34 (0.050)
*144.26 (-200)	*11.52 (6.4)	*326.57 (0.078)
*199.82 (-100)	*12.06 (6.7)	*368.44 (0.088)
*294.26 (70)	-	*426.05 (0.102)
*366.48 (200)	*13.86 (7.7)	*439.61 (0.105)
*477.59 (400)	*15.48 (8.6)	*460.55 (0.110)
*588.70 (600)	*15.84 (8.8)	*476.29 (0.114)
*699.82 (800)	*16.02 (8.9)	-
*810.93 (1000)	*16.38 (9.1)	-
*922.04 (1200)	*16.74 (9.3)	-
*1033.15 (1400)	*17.28 (9.6)	-
*1144.26 (1600)	*17.64 (9.8)	-
*1255.37 (1800)	*18.00 (10.0)	-
*1366.48 (2000)	*18.54 (10.3)	-

(Ref. 6, Page 608, Table TCD)

Temperature K (°F)	Thermal Conductivity[6] W/m·K (Btu/h·ft·°F)
*294 (70)	*21.8 (12.6)
*311 (100)	*22.3 (12.9)
*339 (150)	*23.2 (13.4)
*366 (200)	*24.0 (13.9)
*394 (250)	*25.1 (14.5)
*422 (300)	*26.0 (15.0)
*450 (350)	*27.0 (15.6)
*477 (400)	*27.9 (16.1)
*505 (450)	*28.7 (16.6)
*533 (500)	*29.4 (17.0)
*561 (550)	*30.3 (17.5)
*589 (600)	*31.0 (17.9)
*616 (650)	*31.8 (18.4)
*644 (700)	*32.7 (18.9)
*672 (750)	*33.6 (19.4)
*700 (800)	*34.3 (19.8)
*728 (850)	*35.3 (20.4)
*755 (900)	*36.1 (20.9)
*783 (950)	*37.2 (21.5)
*811 (1000)	*38.1 (22.0)

Mechanical Properties

(Ref. 1, Page 3, Temperatures Properties Table)

Temperature K (°C)	Tensile Strength MPa	Yield Strength, 0.2% offset MPa	Elongation, %
294 (21)	565	215	48
366 (93)	550	205	47
477 (204)	520	180	45
589 (316)	505	175	46
700 (427)	480	160	48
811 (538)	370	145	40

Poisson's Ratio[2] = 0.32 (Ref. 2, Page 3, Table 2)

(Ref. 5, Page 617, Table TM-4)

Temperature K (°F)	Modulus of Elasticity[5] GPa (10^6 psi)
75 (-325)	*191.7 (27.8)
144 (-200)	*188.2 (27.3)
235 (-100)	*184.8 (26.8)
294 (70)	*179.3 (26.0)
366 (200)	*175.1 (25.4)
422 (300)	*172.4 (25.0)
477 (400)	*170.3 (24.7)
533 (500)	*167.5 (24.3)
589 (600)	*166.2 (24.1)
644 (700)	*163.4 (23.7)
700 (800)	*159.3 (23.1)
755 (900)	*155.8 (22.6)
811 (1000)	*152.4 (22.1)

* Data converted to SI units[9]

1. Allegheny Ludlum Steel 1997. *Technical Data Blue Sheet Allegheny Ludlum AL 400 Nickel-Base Alloy (UNS Desiperate N04400)*. Pittsburgh, PA: Alleghany Ludlum Steel. TIC: 240567
2. International Nickel Company 1969. *Monel alloy 400, 401, 404, R-405, K-500.* U.S.A.: International Nickel Company, Inc. TIC: 240356
3. Lide, D. R. 1995. *CRC Handbook of Chemistry and Physics, 76th Edition 1995-1996.* Boca Raton, FL: CRC Press. TIC: 216194
4. American Society of Testing and Materials 1993. *Standard Specifications for Nickel-Copper Alloys (UNSN04400) Plate, Sheet and Strip*. ASTM B 127-93. Philadelphia, PA: ASTM. TIC: 240028
5. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Codes Section II, Table TM-4, Moduli of Elasticity E of High Nickel Alloys for Given Temperatures*. ASME Designation: ASME Section II, Table TM-4. New York, NY: ASME. TIC: 242717
6. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Codes, Section II-D, Table TCD, Nominal Coefficients of Thermal Conductivity and Thermal Diffusivity*. ASME Designation: ASME Section II-D, Table TCD. New York, NY: ASME. TIC: 239596

7. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Code Section II B SB-127, Specifications for Nickel-Copper Alloys (UNSN04400) Plate, Sheet and Strip.* ASME Designation: ASME Section II B SB-127. New York, NY: ASME. TIC: 239691
8. American Society of Testing and Materials 1994. *Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens.* ASTM Designation: ASTM G1-90. Philadelphia, PA: ASTM. TIC: 238771
9. American Society for Testing and Materials 1997. *Standard Practice for Use of the International System of Units (SI): The Modern Metric System.* ASTM Designation: ASTM SI 10-1997. West Conshohocken, PA: ASTM. TIC: 240989

5.9 Neutronit A976/A978

Density[1] = 7760 kg/m^3 at 20 °C (Ref. 1, Page 2)

Composition by Weight %[1]

(Ref. 1, Page 14)

C	0.04 (max)
Cr	18.5
Ni	13.0
Co	0.20 (max)
B[×]	According to Specifications
Fe	Balance[a]

[×] Most common boron content is values similar to ASTM A887 type B3, B4, and B6
[a] Assumption

Physical Properties

Specific Heat[1,3] (20 °C) = 0.5 J/g·K (Ref. 1, Page 2)

Thermal Conductivity[1] (20 °C) = 10.3 W/m·K (Ref. 1, Page 2)
(130 °C) = 11.7 W/m·K
(260 °C) = 13.4 W/m·K

Coefficient of Thermal Expansion[1] (20-100 °C) = 18.0 x 10^{-6} m/m·K (Ref. 1, Page 2)
(20-200 °C) = 17.5 x 10^{-6} m/m·K
(20-260 °C) = 17.5 x 10^{-6} m/m·K
(20-300 °C) = 17.5 x 10^{-6} m/m·K

Emissivity[2] = 0.57-0.66 (Ref. 2, Page 4-68, Table 4.3.2)
Values for SS 316, repeated heating

Modulus of Elasticity[1,3] (20 °C) = 200 x 10^3 N/mm^2 = 200 GPa (Ref. 1, Page 2)

0.2% Proof Stress[3] = 300 N/mm^2 (min) = 300 Mpa (Ref. 3, Page 3-9, Table 3-5)

Tensile Strength[3] = 600 N/mm^2 (min) = 550 Mpa (Ref. 3, Page 3-9, Table 3-5)

(Ref. 1, Page 15)

Boron Content %	Elongation[1], % min
0.8	19
1.0-1.2	16
1.4-1.6	9
1.6-1.9	6

*Data converted to SI units[4]

1. Bohler Bleche 1996. *Special Sheet and Plate*. Murzzuschlag, Austria: Bohler Bleche. ACC: MOL.19961118.0186
2. Avallone, E. A.; Baumeister, T. 1987. *Mark's Standard Handbook for Mechanical Engineers, 9th Edition*. New York, NY: McGraw-Hill Book Company. TIC: 239873
3. Engineering Resources 1992. *Borated Stainless Steel Application in Spent Fuel Storage Racks*. Reading, PA: Engineering Resources, Inc. TIC: 225730
4. American Society of Testing and Materials 1997. *Standard Practice for Use of the International System of Units (SI): The Modern Metric System*. ASTM Designation: ASTM SI 10-1997. West Conshohocken, PA: ASTM. TIC: 240989

5.10 Zircaloy 2
(UNS R60802)

Density[1] = 6.55 g/cm^3 at 70 °F (Ref. 1, Page 1, Section 2.021)

Composition by Weight %[2]

(Ref. 2, Page 2, Table 2)

Sn	1.20-1.70
Fe	0.07-0.20
Cr	0.05-0.15
Ni	0.03-0.08
O	0.09-0.16
Fe + Cr	0.18-0.38
Zr	Remainder*

*Assumption

Mechanical Properties

Tensile Strength[2,4] = 413 MPa (min) (Ref. 2, Page 3, Table 4)

Yield Strength[2,4], 0.2% offset= 241 MPa (min) (Ref. 2, Page 3, Table 4)

Elongation[2,4] in 2 in. or 50 mm[2,4] = 20 % (min) (Ref. 2, Page 3, Table 4)

Modulus of Elasticity[1] at 70 °F = 14 x 10^6 psi (96.5 GPa)* (Ref. 1, Page 1, Physical Constants)

Poisson's Ratio at 70 °F = 0.31[1]-0.37[4] (Ref. 1, Page 1) - (Ref. 4, Page 666, Table 6)

Neutron Absorption Cross Section[1] at 70 °F = 0.18 barns (Ref. 1, Page 1)

Crystal Structure[1]: Hexagonal (Ref. 1, Page 1)

(Ref. 1, Page 1, Tables 2-3)

Temperature K (°F)	Tensile Strength[1], x 10^3 psi (MPa)			Elongation[1], %	
	60% Cold Rolled	Hot Rolled	Annealed	60% Cold Rolled	Hot Rolled
*88.70 (-300)	170 (1172) *	135 (931) *	130 (896) *	9.5	14
*199.82 (100)	134 (923) *	105 (724) *	95 (655) *	6	11
*310.93 (100)	110 (758) *	80 (551) *	68 (469) *	4	9
*422.04 (300)	90 (620) *	63 (434) *	48 (331) *	3	7
*533.15 (500)	75 (517) *	50 (345) *	34 (234) *	3	5
*644.26 (700)	63 (434) *	42 (289) *	26 (179) *	3	4
*755.37 (900)	-	32 (221) *	22 (152) *	3	3

Forged (vacuum melted) (80% reduced by forging, 97% reduced by rolling, 5% cold reduced, annealed at 1550 °F)

(Ref. 1, Page 1, Table 1)

Temperature K (°F)	Direction of Test	Tensile Strength[1] MPa (x 10^3 psi)	Yield Strength[1] (0.2%) MPa (psi)
Room Temperature	Longitudinal	*503-545 (73-79)	*296-379 (43-55)
	Transversal	*503-572 (73-83)	*448-517 (65-75)
533.15 (500)	Longitudinal	*276-303 (40-44)	*145-186 (21-27)
	Transversal	*255-324 (37-47)	*186-283 (27-41)

Thermal Properties

Thermal Coefficient of Expansion[1] (70-660 °F) = 3.6 x 10^{-6} /°F (Ref. 1, Page 1)
(294-622 K) = 6.48 x 10^{-6} /K

Thermal Coefficient of Expansion[1] (room temperature-1290 °C) = 6.5 x 10^{-6} /°C
(room temperature-1563 K) = 6.4 x 10^{-6} /K

(Ref. 3, Page 599, Appendix 9)

Temperature K (°C)	Thermal Conductivity[3] W/m·K (cal/s/cm·°C)
*348 (75)	*14615.55 (34.932)
*373 (100)	*14096.73 (33.692)
*422 (149)	*14010.12 (33.485)
*533 (260)	*13923.52 (33.278)
*573 (300)	*14010.12 (33.485)

Specific Heat[4] = 285 J/kgK (Ref. 4, Page 666, Table 6)

*Data converted to SI units[5]

1. ASM International 1967. *Zircaloy-2, Nuclear Reactor Alloy*. Upper Montclair, NJ: ASM International. TIC: 239929
2. American Society for Testing and Materials 1991. *Standard Specification for Wrought Zirconium Alloy Seamless Tubes for Nuclear Reactor Fuel Cladding*. ASTM Designation: ASTM B 811-90. Philadelphia, PA: ASTM. TIC: 239780
3. Ma, Benjamin M. 1983. *Nuclear Reactor Materials and Applications*. New York, NY: Van Nostrand Reinhold Company. TIC: 241053
4. ASM International 1990. *Metals Handbook 10th Edition, Volume 2, Properties and Selection: Nonferrous Alloys and Special-Purpose Materials*. U.S.A.: ASM International. TIC: 239807
5. American Society of Testing and Materials 1997. *Standard Practice for Use of the International System of Units (SI): The Modern Metric System*. ASTM Designation: ASTM SI 10-1997. West Conshohocken, PA: ASTM. TIC: 240989

5.11 Zircaloy 4
(UNS R60804)

Density[1] = 6560 kg/m^3 (Ref. 1, Page 666, Table 6)

Composition by Weight %[2]

(Ref. 2, Page 2, Table 2)

Sn	1.20-1.70
Fe	0.18-0.24
Cr	0.07-0.130000
O	0.09-0.16
Fe + Cr	0.28-0.37
Zr	Remainder*

*Assumtion

Mechanical Properties

Tensile Strength[1,2] = 414 MPa (min) (60 ksi) (Ref. 2, Page 3, Table 4)

Yield Strength[1,2] = 241 MPa (min) (35 ksi) (Ref. 2, Page 3, Table 4)

Elongation[1,2] in 2 in. or 50 mm = 20% (min) (Ref. 2, Page 3, Table 4)

Modulus of Elasticity[1] = 99.3 GPa (14.4 x 10^6 psi) (Ref. 1, Page 666, Table 6)

Poisson's Ratio[1] = 1.37 (Ref. 1, Page 666, Table 6)

*Data converted to SI units[3]

---

1. ASM International 1990. *Metals Handbook 10th Edition, Volume 2, Properties and Selection: Nonferrous Alloys and Special-Purpose Materials.* U.S.A.: ASM International. TIC: 239807
2. American Society for Testing and Materials 1991. *Standard Specification for Wrought Zirconium Alloy Seamless Tubes for Nuclear Reactor Fuel Cladding.* ASTM Designation: ASTM B 811-90. Philadelphia, PA: ASTM. TIC: 239780
3. American Society of Testing and Materials 1997. *Standard Practice for Use of the International System of Units (SI): The Modern Metric System.* ASTM Designation: ASTM SI 10-1997. West Conshohocken, PA: ASTM. TIC: 240989

5.12 Titanium Grade 7

(Ti Code 7, UNS R52400)

Density[2] = 4500-4540 kg/m^3 at 20 °C (Ref. 2, Page 379)

Composition in Weight %[1,2,7]

(Ref. 6, Page 319, Table 1)

N	0.03 (max)
C	0.10 (max)
H	0.015 (max)
O	0.25 (max)
Fe	0.30 (max)
Pd	0.12-0.25
Residuals (each)	0.1 (max)
Residuals (total)	0.4 (max)
Ti	Remainder

Mechanical Properties

(Ref. 6, Page 321, Table 3), (Ref. 2, Page 375, Table 3)

Temperature K (°F)	Tensile Strength MPa (ksi)	Yield Strength, 0.2% offset, MPa (ksi)	Elongation, in 50 mm or 2 in., %
Room Temperature[6]	345 (50)[6]	275-450 (40-65)[6]	20[6]
477 *(400)[2]	207-228 (30-33)[2]	138-152 (20-22)[2]	38-45[2]
589 *(600)[2]	172-207 (25-30)[2]	90-124 (13-18)[2]	30-38[2]
699 *(800)[2]	131-186 (19-27)[2]	76-103 (11-15)[2]	24-28[2]
811 *(1000)[2]	103-138 (15-20)[2]	62-76 (9-11)[2]	30-35[2]

(Ref. 4, Page 617, Table TM-5)

Temperature K (°C) (°F)	Modulus of Elasticity Gpa (x 10^6 psi)
*294 (21) (70)	*106.87 (15.5)
*366 (93) (200)	*103.42 (15.0)
*422 (149) (300)	*100.66 (14.6)
*477 (204) (400)	*96.53 (14.0)
*533 (260) (500)	*91.70 (13.3)
*589 (316) (600)	*86.87 (12.6)
*644 (371) (700)	*82.04 (11.9)
*700 (427) (800)	*77.22 (11.2)

Poisson's Ratio = 0.32 (Unalloyed Titanium) (Ref. 8, Page 618, Table NF-1)

Thermal Properties

Specific Heat[7] = 544.28 J/kg·K at 100 °C (0.13 Btu/lb·°F at 212 °F) (Ref. 7, Page 620, Table NF-2)

Emissivity[2] = 0.13-0.31 (depending on surface oxidation state) (Ref. 2, Page 374)

Crystal Structure[2]: Close packed hexagonal (below 890 °C); (Ref. 2, Page 375)
Body centered cubic (above 913 °C)

(Ref. 3, Page 611, Table TCD)

Temperature K (°F)	Thermal Conductivity[3] W/m·K (Btu/h·ft·°F)
*294 (70)	*21.9 (12.68)
*311 (100)	*21.7 (12.52)
*339 (150)	*21.2 (12.25)
*366 (200)	*20.8 (12.00)
*394 (250)	*20.5 (11.85)
*422 (300)	*20.3 (11.72)
*450 (350)	*20.1 (11.60)
*477 (400)	*19.8 (11.45)
*505 (450)	*19.6 (11.35)
*533 (500)	*19.5 (11.29)
*561 (550)	*19.4 (11.23)
*589 (600)	*19.4 (11.20)
*616 (650)	*19.3 (11.17)
*644 (700)	*19.3 (11.15)
*672 (750)	*19.3 (11.18)
*700 (800)	*19.4 (11.20)
*728 (850)	*19.4 (11.23)
*755 (900)	*19.5 (11.30)
*783 (950)	*19.7 (11.36)
*811 (1000)	*19.8 (11.43)
*839 (1050)	*19.9 (11.51)
*866 (1100)	*20.0 (11.58)

(Ref. 5, Page 598-599, Table TE-5)

Temperature K °C (°F)	Mean Coefficient of Thermal[5u] Expansion x 10^{-6}/K (x 10^{-6} in/in·°F)
*311 (38) *(100)	8.39 (4.66)
*339 (65) *(150)	8.46 (4.70)
*366 (93) *(200)	8.55 (4.75)
*394 (121) *(250)	8.62 (4.79)
*422 (149) *(300)	8.69 (4.83)
*450 (177) *(350)	8.77 (4.87)
*477 (204) *(400)	8.84 (4.91)
*505 (232) *(450)	8.91 (4.95)
*533 (260) *(500)	9.00 (5.00)
*561 (288) *(550)	9.05 (5.03)
*589 (315) *(600)	9.14 (5.08)
*616 (343) *(650)	9.22 (5.12)
*644 (371) *(700)	9.29 (5.16)
*672 (399) *(750)	9.36 (5.20)
*700 (427) *(800)	9.43 (5.24)

[u]Unalloyed Titanium Grade 2 corresponds to Ti-Pd Grade 7. Hence data for Unalloyed Titanium Grade 2 has been used. Refer to p. 379 of Reference 2.

*Data converted to SI units[9]

1. American Society for Testing and Materials 1996. *Standard Specification for Titanium and Titanium Alloy Strip, Sheet and Plate*. ASTM Designation: ASTM B 265-95a. Philadelphia, PA: ASTM. TIC: 239717
2. American Society for Metals 1980. *Metals Handbook 9th Edition. Properties and Selection: Stainless Steel, Test Materials and Special-Purpose Metals*. Materials Park, OH: American Society for Materials. TIC: 209801
3. American Society of Mechanical Engineers 1995. *ASME Boiler and Pressure Vessel Codes, Section II, Table TCD, Nominal Coefficients of Thermal Conductivity and Thermal Diffusivity*. ASME Section II, Table TCD. New York, NY: American Society of Mechanical Engineers. TIC: 239596
4. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Codes, Section II, Table TM-5, Moduli of Elasticity E of Unalloyed Titanium for Given Temperatures*. ASME Designation: ASME Section II, Table TM-5. New York, NY. ASME. TIC: 242717

5. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Codes, Section II, Table TE-5, Nominal Coefficients of Thermal Expansion for Titanium and Titanium Alloys*. ASME Designation: ASME Section II, Table TE-5. New York, NY: ASME. TIC: 239686
6. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Code. Section II B SB-265, Specification for Titanium and Titanium Alloy Strip, Sheet and Plate*. ASME Designation: ASME Section II SB-265. New York, NY: ASME. TIC: 239694
7. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Codes, ASME Section II-D 95, Table NF-2, Typical Mechanical Properties of Materials*. ASME Section II, Table NF-2. New York, NY: ASME. TIC: 239587
8. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Codes, ASME Section II-D 95, Table NF-1, Typical Mechanical Properties of Materials*. ASME Section II, Table NF-1. New York, NY: ASME. TIC: 239585
9. American Society of Testing and Materials 1997. *Standard Practice for Use of the International System of Units (SI): The Modern Metric System*. ASTM Designation: ASTM SI 10-1997. West Conshohocken, PA: ASTM. TIC: 240989

5.13 Titanium Grade 12

(Ti Code 12, UNS R53400)

Density[2] = 4520 kg/m^3 at 20 °C (Ref. 2, Page 381)

Composition in Weight %[1,3]

(Ref. 1, Page 111, Table 1)

N	0.03 (max)
C	0.08 (max)
H	0.015 (max)
O	0.25 (max)
Fe	0.30 (max)
Mo	0.2-0.4
Ni	0.6-0.9
Residuals (each)	0.1 (max)
Residuals (total)	0.4 (max)
Ti	Balance[a]

[a]Assumption

Mechanical Properties

(Ref. 2, Page 381, Table 8)

Temperature K (°F)	Tensile Strength MPa (ksi)	Yield Strength, 0.2% offset, MPa (ksi)	Elongation, in 50 mm or 2 in., %
*298 (77)	510 (74)	415 (60)	33
*477 (400)	345 (50)	250 (36)	37
*589 (600)	325 (47)	205 (30)	32

Modulus of Elasticity[2] = 16x10^6 psi (110.3 MPa) (Tension) (Ref. 2, Page 381)

Poisson's Ratio[2] = 0.33 (Ref. 2, Page 381)

Thermal Properties

Specific Heat[2] = 540 J/kg·K (at 75 °F) (Ref. 2, Page 381)

Coefficient of Thermal Expansion[2] = 9.5 μm/m·K (at 32-600 °F) (Ref. 2, Page 381)

Thermal Conductivity[2] = 19.0 W/m·K at 20 °C (Ref. 2, Page 381)

Crystal Structure[2]: Equiaxed or acicular alpha with minor amounts of beta. (Ref. 2, Page 381)

*Data converted to SI units[4]

---

1. American Society for Testing and Materials 1995. *Titanium and Titanium Alloy Strip, Sheet and Plate*. ASTM Designation: ASTM B 265-95a. Philadelphia, PA: ASTM. TIC: 239717
2. American Society for Metals 1980. *Metals Handbook 9th Edition, Properties and Selection: Stainless Steels, Materials and Special-Purpose Metals*. Metals Park, OH: American Society for Metals. TIC: 209801
3. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Code, Section II B SB-265, Specification for Titanium and Titanium Alloy Strip, Sheet and Plate*. ASME Designation: ASME Section II SB-265. New York, NY: ASME. TIC: 239694
4. American Society of Testing and Materials 1997. *Standard Practice for Use of the International System of Units (SI): The Modern Metric System*. ASTM Designation: ASTM SI 10-1997. West Conshohocken, PA: ASTM. TIC: 240989

5.14 Titanium Grade 16

(Ti Code 16, UNS R52402)

Density[2] = *4512 kg/m^3 (0.163 lb/in^3) (Ref. 2, Page 620, Table NF-2)

Composition in Weight %[1,3]

(Ref. 1, Page 111, Table 1)

N	0.03 (max)
C	0.08 (max)
H	0.015 (max)
O	0.25 (max)
Fe	0.30 (max)
Pd	0.04-0.080
Residuals (each)	0.1 (max)
Residuals (total)	0.4 (max)
Ti	Balance

Mechanical Properties

Tensile Strength[1,3] = 345 MPa (min) (Ref. 1, Page 112, Table 3)

Yield Strength[1,3] 0.2% offset = 275 MPa (min) (Ref. 1, Page 112, Table 3)
= 450 MPa (max) (Ref. 1, Page 112, Table 3)

Elongation in 2 in. or 50 mm = 20% (min) (Ref. 4, Page 618, Table NF-1)

Poisson's Ratio[4] = 0.32 (Ref. 4, Page 618, Table NF-1)

Thermal Properties

Specific Heat[2] = 0.13 Btu/lb·°F at 212 °F (544.28 J/kg·K at 373 K)
(Ref. 2, Page 620, Table NF-2)

*Data converted to SI units[5]

1. American Society for Testing and Materials 1996. *Standard Specification for Titanium and Titanium Alloy Strip, Sheet and Plate*. ASTM Designation: ASTM B 265-95a. Philadelphia, PA: ASTM. TIC: 239717

2. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Codes, Section II B SB-265, Table NF-2, Typical Physical Properties of Materials.* ASME Designation: ASME Section II, Table NF-2. New York, NY: ASME. TIC: 239587
3. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Code, Section II B SB-265, Specification for Titanium and Titanium Alloy Strip, Sheet and Plate.* ASME Designation: ASME Section II SB-265. New York, NY: ASME. TIC: 239694
4. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Codes, ASME Section II, Table NF-1, Typical Mechanical Properties of Materials.* ASME Designation: ASME Section II, Table NF-1. New York, NY: ASME. TIC: 239585
5. American Society of Testing and Materials 1997. *Standard Practice for Use of the International System of Units (SI): The Modern Metric System.* ASTM Designation: ASTM SI 10-1997. West Conshohocken, PA: ASTM. TIC: 240989

5.15 Aluminum 1100
(UNS A91100)

Density[1,3,10,11] = 2710 kg/m^3 (Ref. 1, Page 65)

Composition in Weight %[2,7]

(Ref. 2, Page 7, Table 1)

Al	99 (min)
Cu	0.05-0.20
Si+Fe	0.95
Mn	0.05 (max)
Zn	0.10 (max)
Residuals (each)	0.05 (max)
Residuals (total)	0.15 (max)

Thermal Properties

(Ref. 8, Page 593, Table TE-2)

Temperature K (°F)	Mean Coefficient of Thermal Expansion[8] x 10^{-6}/K (10^{-6}/°F)
*311 (100)	*22.91 (12.73)
*339 (150)	*23.20 (12.89)
*366 (200)	*23.47 (13.04)
*394 (250)	*23.76 (13.20)
*422 (300)	*24.03 (13.35)
*450 (350)	*24.32 (13.51)
*477 (400)	*24.59 (13.66)

(Ref. 6, Page 612, Table TCD)

Temperature K (°F)	Thermal Conductivity[6] W/m·K (Btu/h·ft·°F)
*294 (70)	*230.36 (133.1)
*311 (100)	*228.11 (131.8)
*339 (150)	*224.99 (130.0)
*366 (200)	*222.40 (128.5)
*394 (250)	*220.32 (127.3)
*422 (300)	*218.42 (126.2)
*450 (350)	*216.86 (125.3)
*477 (400)	*215.48 (124.5)

Specific Heat[1,10] = 904 J/kg·K at 293 K (0.216 Btu/lb·°F) (Ref. 1, Page 66)
= *963 J/kg·K at 373 K (0.23 Btu/lb·°F at 212 °F) (Ref. 10, Page 619)

Emissivity[5,4](polished 50-500 °C) = 0.04-0.06 (*323-773 K)
(rough surface 20-50 °C) = 0.06-0.07 (*293-323 K)
(oxidized surface 200-600 °C) = 0.11-0.19 (*473-873 K)
Data for pure aluminum (Ref. 5, Page 10-297)

Mechanical Properties of O temper

Poisson's Ratio[1] = 0.33 at 20 °C

(Ref. 1, Page 65)

Temperature K (°F)	Tensile Strength[1] MPa (ksi)	Yield Strength[1] MPa (ksi)	Elongation[1], %
*77 (-320)	170 (25)	41 (6)	50
*193 (-112)	105 (15)	38 (5.5)	43
*245 (-18)	97 (14)	34 (5)	40
*297 (75)	90 (13)	34 (5)	40
*373 (212)	69 (10)	32 (4.6)	45
*422 (300)	55 (8)	29 (4.2)	55
*477 (400)	41 (6)	24 (3.5)	65
*533 (500)	28 (4)	18 (2.6)	75
*589 (600)	20 (2.9)	14 (2.0)	80
*644 (700)	14 (2.1)	11 (1.6)	85

(Ref. 9, Page 615, Table TM-2)

Temperature K (°F)	Modulus of Elasticity[9] GPa (10^6 psi)
*75 (-325)	*76.53 (11.1)
*144 (-200)	*74.46 (10.8)
*235 (-100)	*72.39 (10.5)
*294 (70)	*68.95 (10.0)
*366 (200)	*66.19 (9.6)
*422 (300)	*63.43 (9.2)
*477 (400)	*59.98 (8.7)
*533 (500)	*55.85 (8.1)

*Data converted to SI units[12]

1. American Society for Metals 1979. *Metals Handbook, 9th Edition, Properties and Selection: Nonferrous Alloys and Pure Metals, Properties of Weight.* Metals Park, OH: American Society for Metals. TIC: 240182
2. American Society of Testing and Materials 1992. *Standard Specification for Aluminum and Aluminum-Alloy Sheet and Plate.* ASTM B 209M 92a. Philadelphia, PA: ASTM. TIC: 240034
3. American Society for Metals 1961. *Metals Handbook, 8th Edition, Properties and Selection of Metals.* Metals Park, OH: American Society for Metals. TIC: 239920
4. Avallone, E. A.; Baumeister, T. 1987. *Mark's Standard Handbook for Mechanical Engineers, 9th Edition.* New York, NY: McGraw-Hill Book Company. TIC: 239873
5. Lide, D. R. 1995. *CRC Handbook of Chemistry and Physics, 76th Edition 1995-1996.* Boca Raton, FL: CRC Press. TIC: 216194
6. American Society of Mechanical Engineers 1995. *ASME Boiler and Pressure Vessel Codes, Section II, Table TCD, Nominal Coefficients of Thermal Conductivity and Thermal Diffusivity.* ASME Section II, Table TCD. New York, NY: American Society of Mechanical Engineers. TIC: 239596.
7. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Codes, Section II, SB-209. Specification for Aluminum and Aluminum-Alloy Sheet and Plate.* ASME Designation: ASME SB-209. New York, NY: ASME. TIC: 239748
8. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Codes, ASME Section II, Table TE-2, Nominal Coefficients of Thermal Expansion for Aluminum Alloys.* ASME Designation: ASME Section II, Table TE-2. New York, NY: ASME. TIC: 239602
9. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Codes, Section II, Table TM-2, Moduli of Elasticity E of Aluminum and Aluminum Alloys for Given Temperatures.* ASME Designation: ASME Section II, Table TM-2. New York, NY: ASME. TIC: 239606
10. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Codes, Section II, Table NF-2, Typical Physical Properties of Materials.* ASME Designation: ASME Section II, Table NF-2. New York, NY: ASME. TIC: 239587
11. American Society of Testing and Materials 1994. *Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens.* ASTM Designation: ASTM G1-90. Philadelphia, PA: ASTM. TIC: 238771
12. American Society of Testing and Materials 1997. *Standard Practice for Use of the International System of Units (SI): The Modern Metric System.* ASTM Designation: ASTM SI 10-1997. West Conshohocken, PA: ASTM. TIC: 240989

5.16 Aluminum 6061
(UNS A96061)

Density[2,4,12] = 2700 -2713 kg/m^3 (Ref. 12, Page 7, Table X1) - (Ref. 2, Page 619, Table NF-2)

Composition in Weight %[1,3,10,11]

(Ref. 1, Page 115)

Si	0.4-0.8
Fe	0.7 (max)
Cu	0.15-0.4
Mn	0.15 (max)
Mg	0.8-1.2
Cr	0.04-0.35
Zn	0.25 (max)
Ti	0.15 (max)
Residuals (each)	0.05 (max)
Residuals (total)	0.15 (max)
Al	Remainder

Thermal Properties

(Ref. 7, Page 612, Table TCD)

Temperature K (°F)	Thermal Conductivity[7] W/m·K (Btu/h·ft·°F)
*294 (70)	*166.3 (96.1)
*311 (100)	*167.7 (96.9)
*338 (150)	*169.6 (98.0)
*366 (200)	*171.3 (99.0)
*394 (250)	*172.7 (98.8)
*422 (300)	*174.1 (100.6)
*450 (350)	*175.3 (101.3)
*477 (400)	*176.4 (101.9)

(Ref. 9, Page 593, Table TE-2)

Temperature K (°F)	Mean Coefficient of Thermal Expansion[9] x 10^{-6}/K (10^{-6}/°F)
*311 (100)	*22.68 (12.60)
*338 (150)	*22.97 (12.76)
*366 (200)	*23.24 (12.91)
*394 (250)	*23.53 (13.07)
*422 (300)	*23.80 (13.22)
*450 (350)	*24.07 (13.37)
*477 (400)	*24.34 (13.52)

Specific Heat[1,2] = 896 J/kg·K at *293 K (20 °C) (Ref. 1, Page 116)
= 963 J/kg·K at 373 K (0.23 Btu/lb·°F at 212 °F) (Ref. 2, Page 619, Table NF-2)

Emissivity[5,6] (polished 50-500 °C) = 0.04-0.06 (*323-773 K)
(rough surface 20-50 °C) = 0.06-0.07 (*293-323 K)
(oxidized surface 200-600 °C) = 0.11-0.19 (*473-873 K)
Data for pure aluminum (Ref. 6, Page 10-297)

Mechanical Properties

(Ref. 3, Page 24, Table 3)

Temper	Thickness in.	Tensile Strength[3] ksi (MPa)	Yield Strength[3] ksi (MPa)	Elongation[3], in 2 in. (min) %
O	0.006-0.007	22 (*151.7) (max)	12 (*82.7) (max)	10
	0.008-0.009	22 (max)	12 (max)	12
	0.010-0.020	22 (max)	12 (max)	14
	0.021-0.128	22 (max)	12 (max)	16
	0.129-0.449	22 (max)	12 (max)	18
	0.500-1.000	22 (max)	-	18
	1.001-3.000	22 (max)	-	16
T4	0.006-0.007	30 (*206.8) (min)	16 (*110.3) (min)	10
	0.008-0.009	30 (min)	16 (min)	12
	0.010-0.020	30 (min)	16 (min)	14
	0.021-0.249	30 (min)	16 (min)	16
T6	0.006-0.007	42 (*289.5) (min)	35 (*241.3) (min)	4
	0.008-0.009	42 (min)	35 (min)	6
	0.010-0.020	42 (min)	35 (min)	8
	0.021-0.249	42 (min)	35 (min)	10

(Ref. 8, Page 615, Table TM-2)

Temperature K (°F)	Modulus of Elasticity[3] GPa (10^6 psi)
*75 (-325)	*76.53 (11.1)
*144 (-200)	*74.46 (10.8)
*200 (-100)	*72.39 (10.5)
*294 (70)	*68.95 (10.0)
*366 (200)	*66.19 (9.6)
*422 (300)	*63.43 (9.2)
*477 (400)	*59.98 (8.7)
*533 (500)	*55.85 (8.1)

Poisson's Ratio[4] = 0.33 (Ref. 4, Page 946)

*Data converted to SI units[13]

1. American Society for Metals 1979. *Metals Handbook, 9th Edition, Properties and Selection: Nonferrous Alloys and Pure Metals.* Materials Park, OH: American Society for Metals. TIC: 209800
2. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Codes, Section II, Table NF-2, Typical Physical Properties of Materials.* ASME Designation: ASME Section II, Table NF-2. New York, NY: ASME. TIC: 239587
3. American Society of Testing and Materials 1992. *Standard Specification for Aluminum and Aluminum-Alloy Sheet and Plate.* ASTM Designation: ASTM B 209 M 92. Philadelphia, PA: ASTM. TIC: 240034
4. Lyman, T.; Boyer, H. E.; Unterweiser, P. M. 1961. *Metals Handbook, 8th Edition, Properties and Selection of Metals.* Metals Park, OH: American Society of Metals. TIC: 239920
5. Avallone, E. A.; Baumeister, T. 1987. *Mark's Standard Handbook for Mechanical Engineers, 9th Edition.* New York, NY: McGraw-Hill Book Company. TIC: 239873
6. Lide, D. R. 1995. *CRC Handbook of Chemistry and Physics, 76th Edition 1995-1996.* Boca Raton, FL: CRC Press. TIC: 216194
7. American Society of Mechanical Engineers 1995. *ASME Boiler and Pressure Vessel Codes, Section II, Table TCD, Nominal Coefficients of Thermal Conductivity and Thermal Diffusivity.* ASME Section II, Table TCD. New York, NY: American Society of Mechanical Engineers. TIC: 239596

8. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Codes, Section II, Table TM-2, Moduli of Elasticity E of Aluminum and Aluminum Alloys for Given Temperatures*. ASME Designation: ASME Section II, Table TM-2. New York, NY: ASME. TIC: 239606
9. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Codes, Section II, Table TE-2, Nominal Coefficient of Thermal Expansion for Aluminum Alloys*. ASME Designation: ASME Section II, Table TE-2. New York, NY: ASME. TIC: 239602
10. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Code, Section II, B SB-209, Specification for Aluminum and Aluminum-Alloy Sheet and Plate*. ASME Designation: ASME Section II, ST-209. New York, NY: ASME. TIC: 239748
11. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Codes, Section II, B SB-308/ SB-308 M, Specification for Aluminum-Alloy 6061-T6, Standard Structural Shapes*. ASME Designation: ASME Section II SB-308 / SB 308M. New York, NY: ASME. TIC: 239716
12. American Society of Testing and Materials 1994. *Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens*. ASTM Designation: ASTM G1-90. Philadelphia, PA: ASTM. TIC: 238771
13. American Society of Testing and Materials 1997. *Standard Practice for Use of the International System of Units (SI): The Modern Metric System*. ASTM Designation: ASTM SI 10-1997. West Conshohocken, PA: ASTM. TIC: 240989

5.17 Aluminum 6063
(UNS A96063)

Density[6] = *2685 kg/m^3 (0.097 lb/in^3) (Ref. 6, Page 619, Table NF-2)

Composition by Weight %[1]

(Ref. 1, Page 117)

Mn	0.10 (max)
Si	0.20-0.60
Cr	0.10 (max)
Fe	0.35 (max)
Cu	0.10 (max)
Mg	0.45-0.90
Zn	0.10 (max)
Ti	0.10 (max)
Residuals (each)	0.05 (max)
Residuals (total)	0.15 (max)
Al	Balance

Mechanical Properties

(Ref. 1, Page 118, Table 85)

Temperature K (°C)	Tensile Strength[1,2] MPa	Yield Strength[1,2] MPa	Elongation[1,2], %
77 (-196)	234	110	44
193 (-80)	179	103	36
245 (-28)	165	97	34
297 (24)	152	90	33
373 (100)	152	97	18
422 (149)	145	103	20
477 (204)	62	45	40
533 (260)	31	24	75
589 (316)	23	17	80
644 (371)	16	14	105

Poisson's Ratio[1] = 0.33 (Ref. 1, Page 117)

(Ref. 7, Page 615, Table TM-2)

Temperature (°F) K (°C)	Modulus of Elasticity[7] GPa
*(-325) 75 *(-198)	76.53
*(-200) 144 *(-129)	74.46
*(-100) 200 *(73)	72.39
*(70) 294 *(21)	68.95
*(200) 366 *(93)	66.19
*(300) 422 *(149)	63.43
*(400) 477 *(204)	59.98
*(500) 533 *(260)	55.85

Thermal Properties

Specific Heat[1,6] = 900 J/kg·K at Room Temperature (Ref. 1, Page 117)
= 963 J/kg·K at *373 K (0.23 Btu/lb·°F at 312°F) (Ref. 6, Page 619, Table NF-2)

Emissivity[3,4]

(polished 50-500 °C) = 0.04-0.06 (*323-773 K)
(rough surface 20-50 °C) = 0.06-0.07 (*293-323 K)
(oxidized surface 200-600 °C) = 0.11-0.19 (*473-873 K)

Data for pure aluminum (Ref. 4, Page 10-297)

(Ref. 5, Page 612, Table TCD)

Temperature K (°F)	Thermal Conductivity[5] W/m·K (Btu/h·ft·°F)
*294 (70)	*209.07 (120.8)
*311 (100)	*208.21 (120.3)
*338 (150)	*207.17 (119.7)
*366 (200)	*206.13 (119.1)
*394 (250)	*204.75 (118.3)
*422 (300)	*204.75 (118.3)
*450 (350)	*204.05 (117.9)
*477 (400)	*203.53 (117.6)

(Ref. 8, Page 593, Table TE-2)

Temperature K (°F)	Mean Coefficient of Thermal Expansion[8], x 10^{-6} /K (10^{-6}/ °F)
*311 (100)	*22.81 (12.67)
*338 (150)	*23.08 (12.82)
*366 (200)	*23.36 (12.98)
*394 (250)	*23.63 (13.13)
*422 (300)	*23.92 (13.29)
*450 (350)	*24.19 (13.44)
*477 (400)	*24.46 (13.59)

*Data converted to SI units[9]

1. American Society for Metals 1979. *Metals Handbook, 9th Edition, Properties and Selection: Nonferrous Alloys and Pure Metals.* Materials Park, OH: American Society for Metals. TIC: 209800
2. Lyman, T.;Boyer, H. E.; Unterweiser, P. M. 1961. *Metals Handbook, 8th Edition, Properties and Selection of Metals.* Metals Park, OH: American Society of Metals. TIC: 239920
3. Avallone, E. A.; Baumeister, T. 1987. *Mark's Standard Handbook for Mechanical Engineers, 9th Edition.* New York, NY: McGraw Hill Book Company. TIC: 239873
4. Lide, D. R. 1995. *CRC Handbook of Chemistry and Physics, 76th Edition 1995-1996.* Boca Raton, FL: CRC Press. TIC: 216194
5. American Society of Mechanical Engineers 1995. *ASME Boiler and Pressure Vessel Codes, Section II, Table TCD, Nominal Coefficients of Thermal Conductivity and Thermal Diffusivity.* ASME Section II, Table TCD. New York, NY: American Society of Mechanical Engineers. TIC: 239596
6. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Codes, Section II, Table NF-2, Typical Physical Properties of Materials.* ASME Designation: ASME Section II, Table NF-2. New York, NY: ASME. TIC: 239587
7. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Codes, Section II, Table TM-2, Moduli of Elasticity E of Aluminum and Aluminum Alloys for Given Temperatures.* ASME Designation: ASME Section II, Table TM-2. New York, NY: ASME. TIC: 239606
8. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Codes, Section II, Table TE-2, Nominal Coefficients of Thermal Expansion for Aluminum Alloys.* ASME Designation: ASME, Section II, Table TE-2. New York, NY: ASME. TIC: 239602

9. American Society of Testing and Materials 1997. *Standard Practice for Use of the International System of Units (SI): The Modern Metric System.* ASTM Designation: ASTM SI 10-1997. West Conshohocken, PA: ASTM. TIC: 240989

5.18 Aluminum 356-T6
(UNS A03560)

Density[3] = *2685 kg/m^3 (0.097 lb/in^3) (Ref. 3, Page 619, Table NF-2)

Composition by Weight %[1,6]

(Ref. 1, Page 2, Table 1)

Si	6.5-7.5
Fe[c]	0.60
Cu	0.25
Mn[c]	0.35
Mg	0.20-0.45
Zn	0.35
Ti	0.25
Residuals (each)	0.05
Residuals (total)	0.15

[c]If iron content exceeds 0.45%, manganese content shall not be less than one half of the iron content.

Mechanical Properties

Tensile Strength[4] = 206.8 MPa (min) (30.0 ksi) (Ref. 4, Table 2)

Yield Strength[1], 0.2% offset = *137.9 MPa (min) (20.0 ksi) (Ref. 1, Page 4, Table 2)

Elongation[1] in 2 in. or 4 diameters, 3% (min) (Ref. 1, Page 4, Table 2)

(Ref. 4, Page 615, Table TM-2)

Temperature K (°C) (°F)	Modulus of Elasticity[4] GPa (x10^6 psi, for temp, °F)
*75 (-198) *(-325)	*78.60 (11.4)
*144 (-129) *(-200)	*76.53 (11.1)
*200 (-73) *(-100)	*74.46 (10.8)
*294 (21) *(70)	*71.02 (10.3)
*366 (93) *(200)	*67.57 (9.8)
*422 (149) *(300)	*65.50 (9.5)
*478 (204) *(400)	*62.05 (9.0)
*533 (260) *(500)	*55.85 (8.1)

Thermal Properties

Specific Heat[3] at *373 K/212 °F = [3]963 J/kg·K (0.23 Btu/lb·°F) (Ref. 3, Page 619, Table NF-2)

(Ref. 2, Page 612, Table TCD)

Temperature K (°F)	Thermal Conductivity[2] W/m·K (Btu/h·ft·°F)	
294 (70)	159.23	(92.0)
311 (100)	160.79	(92.9)
339 (150)	163.04	(94.2)
366 (200)	165.11	(95.4)
394 (250)	166.84	(96.4)
422 (300)	168.57	(97.4)
450 (350)	169.96	(98.2)
478 (400)	171.17	(98.9)

(Ref. 5, Page 593, Table TE-2)

Temperature K (°F)	Mean Coefficient of Thermal Expansion[5], x 10^{-6} /K	Mean Coefficient of Thermal Expansion, x 10^{-6} in/in·°F
311 (100)	20.86	11.59
338 (150)	21.11	11.73
367 (200)	21.37	11.87
394 (250)	21.62	12.01
422 (300)	21.87	12.15
450 (350)	22.12	12.29
477 (400)	22.37	12.43

* Data converted to SI units[7]

1. American Society for Materials and Testing 1992. *Standard Specifications for Aluminum-Alloy Sand Casting*. ASTM Designation: ASTM B26/B26M-92a. Philadelphia, PA: ASTM. TIC: 240036
2. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Codes, Section II, Table TCD, Nominal Coefficients of Thermal Conductivity (TC) and Thermal Diffusivity (TD)*. ASME Designation: ASME Section II, Table TCD. New York, NY: ASME. TIC: 239596

3. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Codes, Section II, Table NF-2, Typical Physical Properties of Materials.* ASME Designation: ASME Section II, Table NF-2. New York, NY: ASME. TIC: 239587
4. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Codes, Section II, Table TM-2, Moduli of Elasticity E of Aluminum and Aluminum Alloys for Given Temperatures.* ASME Designation: ASME Section II, Table TM-2. New York, NY: ASME. TIC: 239606
5. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Codes, Section II, Table TE-2, Nominal Coefficients of Thermal Expansion for Aluminum Alloys.* ASME Designation: ASME, Section II, Table TE-2. New York, NY: ASME. TIC: 239602
6. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Codes, Section II, B SB-26/SB-26M Specification for Aluminum-Alloy Sand Castings.* ASME Designation: ASME Section II, SB-26/SB-26M. New York, NY: ASME. TIC: 239751
7. American Society of Testing and Materials 1997. *Standard Practice for Use of the International System of Units (SI): The Modern Metric System.* ASTM Designation: ASTM SI 10-1997. West Conshohocken, PA: ASTM. TIC: 240989

5.19 Copper C 12200

(UNS C12200, DHP, Phosphorized Copper, Deoxidized Copper)

Density[4,5] = 8940 kg/m^3 at 20 °C (Ref. 4, Page 1010)

Composition by Weight %[4]

(Ref. 4, Page 1010)

Cu+Ag	99.90 (min)
P	0.02

Mechanical Properties

(Ref. 1, Page 263, Table 2)

Temper	Tensile Strength Mpa	Yield Strength MPa	Elongation, in 50 mm or 2 in., %
OS050	220	69	45
OS025	235	76	45
H55	275	220	25
H80	380	345	8

C 12200, bar, O61 temper (annealed)[2]

(Ref. 2, Page 747, Table 26)

Temperature K (°C)	Tensile Strength Mpa	Yield Strength MPa	Elongation, in 50 mm or 2 in., %
297 (24)	215	46	45
195 (-78)	265	46	56
77 (-196)	350	51	62
20 (-253)	440	58	68
4 (-269)	415	54	65

(Ref. 7, Page 616, Table TM-3)

Temperature K (°C) (°F)	Modulus of Elasticity[7] GPa (x 10^{-6} psi, for temp °F)	
*75 (-198) *(-325)	*124.1	(18.0)
*144 (-129) *(-200)	*122.0	(17.7)
*200 (-73) *(-100)	*120.7	(17.5)
*294 (21) *(70)	*117.2	(17.0)
*366 (93) *(200)	*114.5	(16.6)
*422 (149) *(300)	*112.4	(16.3)
*478 (204) *(400)	*110.3	(16.0)
*533 (260) *(500)	*107.6	(15.6)
*589 (316) *(600)	*104.1	(15.1)
*644 (371) *(700)	*100.0	(15.4)

Poisson's Ratio[6] = 0.33 (Ref. 6, Page 618, Table NF-1)

Emissivity[3] = 0.57 (473-873 K) (200-600 °C) (Ref. 3, Page 4-68, Table 4.3.2)
Data for pure copper

Thermal Expansion[4] = 17.7 μin/in·°C (293-573 K) (68-572°F) (Ref. 4, Page 1010)

Specific Heat[4,5] = 385 J/kg·K at 293 K (0.092 cgs at 20 °C) (Ref. 4, Page 1010)
= 377 J/kg·K at 373 K (0.09 Btu/lb·°F at 212 °F) (Ref. 5, Page 619, Table NF-2)

Thermal Conductivity[4] = (196 Btu/h·ft·°F) or 339.2 W/m·K (Ref. 4, Page1011)

*Data converted to SI units[8]

1. American Society for Metals 1979. *Metals Handbook, 9th Edition, Properties and Selection: Non Ferrous Alloys and Pure Metals*. Materials Park, OH: American Society for Metals. TIC: 209800
2. American Society for Metals 1978. *Metals Handbook, 9th Edition, Properties and Selection: Iron and Steel*. Materials Park, OH: American Society for Metals. TIC: 209779
3. Avallone, E. A.; Baumeister, T. 1987. *Mark's Standard Handbook for Mechanical Engineers, 9th Edition*. New York, NY: McGraw Hill Book Company. TIC: 239873

4. Lyman, T.; Boyer, H. E.; Unterweiser, P. M. 1961. *Metals Handbook, 8th Edition, Properties and Selection of Metals.* Metals Park, OH: American Society of Metals. TIC: 239920.
5. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Codes, Section II, Table NF-2, Typical Physical Properties of Materials.* ASME Designation: ASME Section II, Table NF-2. New York, NY: ASME. TIC: 239587
6. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Codes, Section II, Table NF-1, Typical Physical Properties of Materials.* ASME Designation, ASME Section II, Table NF-1. New York, NY: ASME. TIC: 239585
7. American Society of Mechanical Engineers 1995. *Boiler and Pressure Vessel Codes, Section II, Table TM-3, Moduli of Elasticity E of Copper and Copper Alloys for Given Temperatures.* ASME Designation: ASME Section II, Table TM-3. New York, NY: ASME. TIC: 239608
8. American Society of Testing and Materials 1997. *Standard Practice for Use of the International System of Units (SI): The Modern Metric System.* ASTM Designation: ASTM SI 10-1997. West Conshohockon, PA: ASTM. TIC: 240989

5.20 Gadolinium Oxide (Powder)

Density[1] = 7000 kg/m^3 (Ref. 1, Page 683)

Physical Properties

(Ref. 2, Page 239)

Temperature K	Coefficient of Thermal[2] Expansion, x 10^{-6}/K
293	6.6
400	7.0
500	7.3
600	7.7
700	8.0
800	8.3
900	8.6
1000	8.9
1100	9.2
1200	9.5
1300	9.7
1400	10.0

Values stated are ± 15% accurate.

1. Clauser, H. R.; Brady, G. S. 1991. *Materials Handbook, 13th Edition*. New York, NY: McGraw-Hill Book Company. TIC: 103312
2. The Thermophysical Properties Research Center 1970. *Thermophysical Properties of Matter, The TPRC Data Service, Volume 5, Specific Heat – Nonmetallic Solids*. New York, NY: Y. S. Touloukian & E. H. Buy Co. IFI/Plenum. TIC: 239936

5.21 Gadolinium (Metal)

Density[1,2,3] = 7901 kg/m^3 (at 24 °C) (Ref. 1, Page 735)
= 7860 kg/m^3 (Ref. 2, Page 154)

Composition by Weight %[3]

(Ref. 3, Page 1230, Table 3)

Mg	0.01
Ta	0.2
O	0.16
N	0.008
C	0.009
Eu	0.03
Tb	0.03

Crystal Structure[1]: Close-packed hexagonal (Ref. 1, Page 735)

Thermal Properties

Coefficient of Linear Thermal Expansion[1] at 373 K = 9.4 x 10^{-6}/K (100 °C) (Ref. 1, Page 735)

Specific Heat[1] at 298 K = 235.7 J/kg·K (25 °C) (Ref. I, Page 735)

Thermal Conductivity[1] at 298 K = 10.5 W/m·K (25 °C)

Thermal Neutron Cross Section[1] = 40,000 barns (Ref. 1, Page 735)

Mechanical Properties

As-Cast Gadolinium[3]

(Ref. 3, Page 1231, Table 5)

Temperature K (°C)	Tensile Strength psi (MPa)	Yield Strength psi (MPa)	Elongation, in 2 in. or 50 mm, %	Modulus of Elasticity, 10^6 psi (GPa)
Room	26,400 *(182)	25,100 *(173)	7.8	8-14 *(55-97)
*477 (204)	18,000 *(124)	15,600 *(107.6)	6.8	-
*700 (427)	14,100 *(97.2)	13,100 *(90.3)	11.3	-

Worked Gadolinium[3]

(Ref. 3, Page 1231, Table 5)

Temperature K (°C)	Tensile Strength psi (MPa)	Yield Strength psi (MPa)	Elongation, in 2 in. or 50 mm, %
Room	56,500 *(389.6)	39,000 *(268.9)	6.6
*477 (204)	41,800 *(288.2)	30,100 *(207.5)	4.2
*700 (427)	19,200 *(132.4)	14,200 *(97.9)	12.3

Tensile Strength[1] = 122 Mpa (Ref. 1, Page 736)

Yield Strength[1] = 17 Mpa (Ref. 1, Page 736)

Elongation[1] = 47% (Ref. 1, Page 736)

Elastic Modulus at 27 °C[1] = 55.8 GPa (Tension) (Ref. 1, Page 736)

Poisson's Ratio[1] = 0.254 (Ref. 1, Page 736)

*Data converted to SI units[4]

---

1. American Society for Metals 1979. *Metals Handbook 9th Edition, Properties and Selection: Nonferrous Alloys and Pure Metals*. Metals Park, OH: American Society for Metals. TIC: 209800
2. Bauccio, M. 1993. *ASM Metals Reference Book*. Materials Park, OH: American Society for Metals. TIC: 240701
3. Lyman, T.; Boyer, H. E.; Unterweiser, P. M. 1961. *Metals Handbook, 8th Edition, Properties and Selection of Metals*. Metals Park, OH: American Society of Metals. TIC: 239920
4. American Society of Testing and Materials 1997. *Standard Practice for Use of the International System of Units (SI): The Modern Metric System*. ASTM Designation: ASTM SI 10-1997. West Conshohocken, PA: ASTM. TIC: 240989

5.22 Uranium (metal)

Density[1,3] = 1870-1905 kg/m^3 for wrought metal
= 1905 kg/m^3 for α phase at 25 °C (298 K) (Ref. 1 Page 821)
= 1845 kg/m^3 for α phase at 600 °C (Ref. 3, Page 1226, Section C-2)
= 1813 kg/m^3 for β phase at 700 °C (Ref. 3, Page 1226, Section C-2)
= 1791 kg/m^3 for γ phase at 900 °C (Ref. 3, Page 1226, Section C-2)

Thermal Properties

(Ref. 1, Page 821)

Phase	Temperature K	Specific Heat[1] J/kg·K
α	300	117
α	600	145
α	800	172
α	900	190
β	940	179
β	1040	179
γ	1050	160
γ	1300	160

(Ref. 1, Page 821)

Phase	Temperature K	Thermal Conductivity[1] W/m·K
α	10	9.8
α	20	15.8
α	100	2.17
α	200	25.1
α	300	27.6
α	400	29.6
α	600	31.7
α	800	38.8
α	900	41.3
β	1000	43.9
γ	1100	46.3
γ	1200	49.0

(Ref. 1, Page 821)
Coefficient of Linear Thermal Expansion[1]
at 298 K = 12 x 10^{-6}/K (α phase)
at 900 K = 28 x 10^{-6}/K (α phase)
at 1000 K = 28 x 10^{-6}/K (β phase)
between 1175 to 1400 K = 20 x 10^{-6}/K (γ phase)

Mechanical Properties

Tensile Strength[1] = 400 MPa at 293 K (Cast) (Ref. 1, Page 822)

Yield Strength[1], 2% offset = 200 MPa (Ref. 1, Page 822)

Elongation[1,3] = 4% (Ref. 1, Page 822)

Emissivity[2] = 0.54 (Ref. 2, Page 10-298)

Poisson's Ratio[3] = 0.21 (Ref. 3, Page 1226)

Modulus of Elasticity[3] = 24,000,000 psi (165.5 GPa) (Ref. 3, Page 1226)

Absorption Cross Section[4] = 7.6 barns (Ref. 4, Page 360)

*Data converted to SI units[5]

---

1. American Society for Metals 1979. *Metals Handbook 9th Edition, Properties and Selection: Nonferrous Alloys and Pure Metals*. Metals Park, OH: American Society for Metals. TIC: 209800
2. Lide, D. R. 1995. *CRC Handbook of Chemistry and Physics, 76th Edition 1995-1996*. Boca Raton, FL: CRC Press. TIC: 216194
3. Lyman, T.; Boyer, H. E.; Unterweiser, P. M. 1961. *Metals Handbook, 8th Edition, Properties and Selection of Metals*. Metals Park, OH: American Society of Metals. TIC: 239920
4. Lynch, C. T. 1975. *CRC Handbook of Materials Science, Volume III, Nonmetallic Materials and Applications*. Cleveland, OH: CRC Press. TIC: 240575
5. American Society of Testing and Materials 1997. *Standard Practice for Use of the International System of Units (SI): The Modern Metric System*. ASTM Designation: ASTM SI 10-1997. West Conshohocken, PA: ASTM. TIC: 240989

5.23 Uranium Dioxide

Density[1,4,5,6] = 10,960 kg/m^3 (Ref. 1, Page 221, Table 8.1)

Crystal Structure[5]: Face centered cubic (Ref. 5, Page 667)

Thermal Properties

Specific heat[5] (cal/mole·°C) = $18.45+2.431\times10^{-3}\,T - 2.272\times10^{5}\,T^{-2}$ (Ref. 5, Page 668)
T = °C

Thermal Conductivity at 1273 K[1] = 82 x 10^{-4} cal/s/cm·°C (3.43 W/m·K)* (Ref. 1, Page 221, Table 8.1)

(Ref. 5, Page 668)
Coefficient of Linear Expansion[5] (K^{-1}) = 10.8 x 10^{-6} *(293-1199 K) (20-926 °C)
= 9.9 x 10^{-6} *(298-1073 K) (25-800 °C)
= 10 x 10^{-6} *(673-1173 K) (400-900 °C)
= 10.52 x 10^{-6} *(299-1273 K) (26-1000 °C)

(Ref. 2, Page 598, Appendix 9)

Temperature K (°C)	Thermal Conductivity[2] W/m·K (x 10^{-3} cal/s/cm·°C)
*533 (260)	*5.015 (11.988)[a]
*811 (538)	*3.45 (8.268)[a]
*1088 (815)	*3.19 (7.648)[a]
*1423 (1150)	*2.42 (5.788)[a]
*2143 (1870)	*2.24 (5.376)[a]
*533 (260)	*2.50 (5.994)[b]
*811 (538)	*2.19 (5.250)[b]
*1088 (815)	*1.98 (4.750)[b]

a. Unirradiated corrected to theoretical density
b. Irradiated, startups

Mechanical Properties

Modulus of Elasticity[5] = 28 x 10^6 psi *(193 GPa) at RT (Ref. 5, Page 668)
= 24 x 10^6 psi (165.5 GPa) at 1073 K (800 °C)

Compressive Strength[5] = 4.14-9.65 kbars (Ref. 5, Page 668)

Poisson's Ratio[5] = 0.302 at RT (Ref. 5, Page 669)

Absorption Cross Section[6] = 7.6 barns (Ref. 6, Page 360)

Emissivity[3] = 0.30 (Probable value for oxide formed on smooth metal) (Ref. 3, Page 10-298)

*Data converted to SI units[7]

---

1. Clauss, F. J. 1969. *Engineer's Guide to High-Temperature Materials, Properties of Oxide*. Reeding, MA: Addison - Wesley Publishing Company. TIC: 239825
2. Benjamin, M. M. 1983. *Nuclear Reactor Materials and Application.* New York, NY: Routledge Publishing Inc. TIC: 240576
3. Lide, D. R. 1995. *CRC Handbook of Chemistry and Physics, 76th Edition 1995-1996.* Boca Raton, FL: CRC Press. TIC: 216194
4. American Society of Testing and Materials 1990. *Standard Specification for Sintered Uranium Dioxide Pellets.* ASTM Designation: ASTM C 776-89. Philadelphia, PA: ASTM. TIC: 240038
5. Belle, J. 1961. *Uranium Dioxide: Properties and Nuclear Applications*. Washington, D.C.: U.S. Atomic Energy Commission. TIC: 239923
6. Lynch, C. T. 1975. *CRC Handbook of Materials Science, Volume III, Nonmetallic Materials and Applications*. Cleveland, OH: CRC Press. TIC: 240575
7. American Society of Testing and Materials 1997. *Standard Practice for Use of the International System of Units (SI): The Modern Metric System*. ASTM Designation: ASTM SI 10-1997. West Conshohocken, PA: ASTM. TIC: 240989

5.24 Uranium Carbide (UC)

Density[1] =13,630 kg/m^3 (theoretical) (Ref. 2, Page 296, Table 8-1)
= 12,970 kg/m^3 (unirradiated) (Ref. 1, Page 598, Appendix 9)

Thermal Properties

(Ref. 1, Page 598, Appendix 9)

Temperature °C	Thermal Conductivity W/m·K (x 10^{-3} cal/s/cm·°C)
260	*22.15 (53.824)
538	*20.60 (49.235)
815	*20.29 (48.491)
1870	*20.01 (47.830)

(Ref. 1, Page 185, Table 7.3)

Temperature K (°C)	Thermal Conductivity[1] W/m·K (x 10^{-3} cal/s/cm·°C)
*298 (25)	*32.43 (77.50)
*318 (45)	*32.64 (78.0)
*333 (60)	*34.31 (80.20)
*388 (115)	*31.05 (74.20)
*468 (195)	*25.56 (61.10)
*538 (265)	*25.56 (50.10)
*773 (500)	*7.32 (17.50)
*1023 (750)	*7.11 (17.0)
*1273 (1000)	*7.57 (18.10)

Thermal Conductivity[2] *(473-1273 K) = 23 W/m·°C (200-1000 °C)
(Ref. 2, Page 296, Table 8-1)

Specific Heat[2] at *373 K = 146 J/kg·°C (Ref. 2, Page 296, Table 8-1)

Linear Coefficient of Expansion[2] = 11.1 x 10^{-6} /K (Ref. 2, Page 296, Table 8-1)

Crystal Structure[2]: Face centered cubic (Ref. 2, Page 296, Table 8-1)

Mechanical Properties

Tensile Strength[2] = 62 Mpa (Ref. 2, Page 296, Table 8-1)

Modulus of Elasticity[1] = 4.5×10^5 kg/cm^2 = 44.13 GPa (Ref. 1, Page 184, Table 7.2)

Yield Strength (0.2%)[1] = 70-90 kg/cm^2 = *6.9-8.83* Mpa (Ref. 1, Page 184, Table 7.2)

*Data converted to SI units[3]

---

1. Ma, B. M. 1983. *Nuclear Reactor Materials and Applications*. New York, NY: Van Nostrand Reinhold Company. TIC: 240576
2. Todreas, N. E.; Kazimi, M. S. 1989. *Nuclear Systems I, Thermal Hydraulic Fundamentals*. New York, NY: Hemisphere Publishing Corporation. TIC: 226511
3. American Society of Testing and Materials 1997. *Standard Practice for Use of the International System of Units (SI): The Modern Metric System.* ASTM Designation: ASTM SI 10-1997. West Conshohocken, PA: ASTM. TIC: 240989

5.25 Uranium Aluminide (UAl_2, UAl_3 and UAl_4)

UAl_2
Density[1] = 8100 kg/m^3 (Ref. 1, Page 142, Table 6.4)

Crystal Structure[1]: Face centered cubic (Ref. 1, Page 142, Table 6.4)

UAl_3
Density[1] = 6700 kg/m^3 (Ref. 1, Page 142, Table 6.4)

Crystal Structure[1]: Simple cubic (Ref. 1, Page 142, Table 6.4)

UAl_4
Density[1] = 6000 kg/m^3 (Ref. 1, Page 142, Table 6.4)

Crystal Structure[1]: Orthorhombic (Ref. 1, Page 142, Table 6.4)

---

1. Ma, B. M. 1983. *Nuclear Reactor Materials and Applications*. New York, NY: Van Nostrand Reinhold Company. TIC: 240576

5.26 Uranium Silicide (U_3Si, USi and U_3Si_2)

U_3Si

Density[1] = 15,580 kg/m^3 (theoretical) (Ref. 1, Page 200, Table 7.7)

Linear Thermal Expansion Coefficient[1] *(293-473 K) (20-200 °C) = 13 x 10^{-6}/°C (Ref. 1, Page 200, Table 7.7)

Thermal Conductivity[1] at *298 K (25 °C) = 0.036 cal/s/cm·°C = *15.06 W/m·K (Ref. 1, Page 200, Table 7.7)

Yield Strength (tension)[1] at *298 K (25 °C) = 540 kg/cm^2 = 52.96 Mpa (Ref. 1, Page 200, Table 7.7)

Ultimate Strength[1] at *298 K (25 °C) = 4000 kg/cm^2 = 392.3 Mpa (Ref. 1, Page 200, Table 7.7)

Crystal Structure[1]: Body centered tetragonal (Ref. 1, Page 167, Table 7.1)

USi

Density[1] = 10,400 kg/m^3 (Ref. 1, Page 167, Table 7.1)

Crystal Structure[1]: Orthorhombic (Ref. 1, Page 167, Table 7.1)

U_3Si_2

Density[1] = 12,200 kg/m^3 (Ref. 1, Page 200, Table 7.7)

Linear Thermal Expansion Coefficient *(293-473 K)[1] = 15.5 x 10^{-6}/°C (Ref. 1, Page 200, Table 7.7)

Thermal Conductivity[1] at *298 K = 0.035 cal/s/cm·°C = *14.6 W/m·K (Ref. 1, Page 200, Table 7.7)

Yield Strength (tension)[1] at *298 K = 510-560 kg/cm^2 = *50-55 Mpa (Ref. 1, Page 200, Table 7.7)

Ultimate Strength[1] at *298 K = 3500-4200 kg/cm^2 = 343-412 Mpa
(Ref. 1, Page 200, Table 7.7)

*Data converted to SI units[2]

---

1. Ma, B. M. 1983. *Nuclear Reactor Materials and Applications*. New York, NY: Van Nostrand Reinhold Company. TIC: 240576
2. American Society of Testing and Materials 1997. *Standard Practice for Use of the International System of Units (SI): The Modern Metric System*. ASTM Designation: ASTM SI 10-1997. West Conshohocken, PA: ASTM. TIC: 240989

5.27 Hafnium

Density[1,3,4,5] = 13,090-13,310 kg/m^3 (Ref. 3, Page 1205) - (Ref. 1, Page B-82)

Composition by Weight %[2]

(Ref. 2, Page 715, Table 1)

Al	0.010
C	0.015
Cr	0.010
Cu	0.010
H	0.0025
Fe	0.050
Mb	0.0020
Ni	0.0050
Nb	0.010
N	0.010
O	0.040
Si	0.010
Ta	0.020
Sb	0.0050
Ti	0.010
W	0.0150
U	0.0010
Va	0.0050
Hf	Balance

Thermal Properties

Specific Heat[4] at 298.15 K= 6.15 cal/(g-atom·K) =*25732 J/kg·K
(Ref. 4, Page 755, Table 1)
at 1300 K = 7.98 cal/(g-atom·K) = *33388 J/kg·K
(Ref. 4, Page 755, Table 1)

Coefficient of Linear Thermal Expansion[3,4,5] *(293-473 K) = 5.9 x 10^{-6}/°C
(Ref. 4, Page 755, Table 1)

Crystal Structure[3,4,5]: (Ref. 4, Page 755, Table 1)
Close packed hexagonal (α)
Body centered cubic (β)

Thermal Neutron Cross Section[4] (Ref. 4, Page 755, Table 1)

Absorption[4] = 105 ± 5 barns (Ref. 4, Page 755, Table 1)

Scattering[4] = 8 ± 2 barns (Ref. 4, Page 755, Table 1)

Fast Neutron Total Cross Section[4] = 7 barns (Ref. 4, Page 755, Table 1)

Mechanical Properties

(Ref. 2, Page 716, Table 3)

Condition	Temperature K (°C)	Tensile Strength[2] Mpa (ksi)	Yield Strength[2] MPa	Elongation[2], in 2 in. (50 mm), %
Longitudinal & annealed	RT	*400 (58)	*152 (22)	20
	*589 (316)	*172 (25)	*76 (11)	25
Transverse & annealed	RT	*310 (45)	*172 (25)	25
	*589 (316)	*158 (23)	*96 (14)	35

For Grade R1

(Ref. 3, Page 1206)

Temperature K (°F)	0.2% Yield Strength[3] psi (MPa)	Tensile Strength[3] psi (MPa)	Elongation[3], in 2 in., %
Room	33,600 *(231.7)	64,800 *(447)	23
422 (300)	28,700 *(197.9)	53,200 *(367)	29
533 (500)	22,300 *(153.7)	42,000 *(289.5)	36
644 (700)	15,700 *(108.2)	33,700 *(232.3)	43

Modulus of Elasticity[4] at Room Temperature = 19.8×10^6 psi = *136.5 GPa
(Ref. 4, Page 755, Table 1)

*Data converted to SI units[6]

1. Weast, R. C. 1979. *Handbook of Chemistry and Physics, 60th Edition, 1979-1980.* Boca Raton, FL: CRC Press. TIC: 239952

2. American Society of Testing and Materials 1991. *Standard Specification for Hafnium and Hafnium Alloy Strip, Sheet, and Plate*. ASTM Designation: ASTM B 776-91. Philadelphia, PA: ASTM. TIC: 239775
3. Lyman, T.; Boyer, H. E.; Unterweiser, P. M. 1961. *Metals Handbook, 8th Edition, Properties and Selection of Metals.* Metals Park, OH: American Society of Metals. TIC: 239920
4. Kirk, R. E.; Othmer, D. F. 1970. *Encyclopedia of Chemical Technology, Volume 4.* New York, NY: John Wiley & Sons Inc. TIC: 239924
5. American Society for Testing and Materials 1997. *Metals Handbook, 10th Edition, Volume II, Properties and Selection: Nonferrous Alloys and Special-Purpose Materials, Specific Metals and Alloys*. Materials Park, OH: American Society for Metals. TIC: 239807
6. American Society of Testing and Materials 1997. *Standard Practice for Use of the International System of Units (SI): The Modern Metric System*. ASTM Designation: ASTM SI 10-1997. West Conshohocken, PA: ASTM. TIC: 240989

5.28 Boron Carbide

Density[1] = 2520 kg/m^3 (Ref. 1, Page 677)

Composition by Weight %[2]

(Ref. 2, Page 187, Table 1)

Total B	73.0-81.0
Nitric acid-soluble B	0.5 (max)
Water-soluble B	0.2 (max)
Ca	0.3 (max)
Fe	1.0 (max)
Total B + Total C	98.0 (min)
Fluoride	0.000025 (max)
Chloride	0.000075 (max)
Water	0.000750 (max)

Mechanical Properties

Tensile Strength[1] = 22,500 psi at 980 °C = 155.1 Mpa (Ref. 1, Page 677)

Compression Strength[1] = 180 kg/mm^2 = *1.76 x 10^{-3} N/m^2 (Ref. 1, Page 677)

Thermal Properties

Mean Coefficient of Thermal Expansion[3] (β) = 6 x 10^{-6} /°F = *10.8 x 10^{-6} /K*
(Ref. 3, Page 74, Table 2)

*Data converted to SI units[4]

1. Kirk, R. E.; Othmer, D. F. 1970. *Encyclopedia of Chemical Technology, Volume 3.* New York, NY: John Wiley & Sons Inc. TIC: 239926
2. American Society of Testing and Materials 1992. *Specification for Nuclear-Grade Boron Carbide Pellets.* ASTM Designation: ASTM C 751-92. Philadelphia, PA: ASTM. TIC: 239782
3. Kirk, R. E.; Othmer, D. F. 1970. *Encyclopedia of Chemical Technology, Volume 4.* New York, NY: John Wiley & Sons Inc. TIC: 239924
4. American Society of Testing and Materials 1997. *Standard Practice for Use of the International System of Units (SI): The Modern Metric System.* ASTM Designation: ASTM SI 10-1997. West Conshohocken, PA: ASTM. TIC: 240989

5.29 Graphite (Commercial Grade)

Density[3] = 2250 kg/m^3 at 20 °C (Ref. 3, Page 44)

Mechanical Properties

Modulus of Elasticity (tension)[3,4] = 0.7 x 10^6 psi = 4.83 GPa (Ref. 3, Page 48)

Tensile Strength[4] = 100 psi = 689.5 Pa (Ref. 4, Page 360)

Thermal Properties

(Ref. 1, Page 5, Table A2-1)

Temperature K	Specific Heat[1] J/kg·K
400	961
500	1187
600	1370
700	1516
800	1632
900	1723
1000	1796
1100	1854
1200	1901
1300	1940
1400	1972
1500	2000
1600	2024
1700	2040
1800	2066
1900	2083
2000	2100
2100	2115
2200	2129
2300	2142
2400	2154
2500	2165

Coefficient of Linear Thermal Expansion[3] *(293-373 K) (20-100 °C) = *0.6-4.3 μin/in·°C = 0.6-4.3/K (Ref. 3, Page 48)

Thermal Conductivity[4] = 24 W/m·°C (Ref. 4, Page 360, Table 3.6-1)

Total Emissivity[2] at 273-3873 K= 0.7-0.8 (Ref. 2, Page 10-297)

Crystal Structure[3]: Hexagonal (Ref. 3, Page 50)

Absorption Cross Section[4] = 0.004 barns (Ref. 4, Page 360, Table 3.6-1)

*Data converted to SI units[5]

---

1. American Society of Mechanical Engineers 1983. *Standard Practice for Testing Graphite and Boronated Graphite Components for High-Temperature Gas-Cooled Nuclear Reactors.* ASTM Designation: ASTM C 781-83. Philadelphia, PA: ASTM. TIC: 240037
2. Lide, D. R. 1995. *CRC Handbook of Chemistry and Physics, 76th Edition 1995-1996.* Boca Raton, FL: CRC Press. TIC: 216194
3. Lyman, T.; Boyer, H. E.; Unterweiser, P. M. 1961. *Metals Handbook, 8th Edition, Properties and Selection of Metals.* Metals Park, OH: American Society of Metals. TIC: 239920
4. Lynch, C. T. 1975. *CRC Handbook of Materials Science, Volume III, Nonmetallic Materials and Applications.* Cleveland, OH: CRC Press. TIC: 240575
5. American Society of Testing and Materials 1997. *Standard Practice for Use of the International System of Units (SI): The Modern Metric System.* ASTM Designation: ASTM SI 10-1997. West Conshohocken, PA: ASTM. TIC: 240989

5.30 Graphite (Nuclear Grade A)

Bulk Density[1] = 1730 kg/m^3 (Ref. 1, Page 367, Table 3.6-6)

Thermal Properties

Thermal Conductivity, (Ref. 1, Page 367, Table 3/6-6)
Longitudinal[1] = 141 Btu/h·ft·°F = *244.0 W/m·K
Transverse[1] = 62 Btu/h·ft·°F = *107.3 W/m·K

Coefficient of Thermal Expansion[1], (Ref. 1, Page 367, Table 3.6-6)
Longitudinal = 0.2 x 10^{-6}/°F = *36 x 10^{-6}/K
Transverse = 1.9 x 10^{-6}/°F = *34.2 x 10^{-6}/K

Mechanical Properties

Tensile Strength[1] = 1400 psi (longitudinal) = 9.7 MPa* (Ref. 1, Page 367, Table 3.6-6)

Compressive Strength[1] = 5000 psi (longitudinal) =34.5 Mpa (Ref. 1, Page 367, Table 3.6-6)

Elastic Modulus[1], (Ref. 1, Page 367, Table 3.6-6)
Longitudinal = 2.3 x 10^6 psi = 16 GPa
Transverse = 0.8 x 10^6 psi = 5.5 GPa

Slow Neutron Absorption, cross section/carbon atom[1] = 3.95 x 10^{-27} mb (Ref. 1, Page 367, Table 3.6-6)

*Data converted to SI units[2]

---

1. Lynch, C. T. 1975. *CRC Handbook of Materials Science, Volume III, Nonmetallic Materials and Applications*. Cleveland, OH: CRC Press, Inc. TIC: 240575
2. American Society of Testing and Materials 1997. *Standard Practice for Use of the International System of Units (SI): The Modern Metric System.* ASTM Designation: ASTM SI 10-1997. West Conshohocken, PA: ASTM. TIC: 240989

5.31 INCONEL 718

Density[1,2] = 8190 kg/m^3 (Ref. 1, Page 1276, Table 2.7.6)

Composition by Weight %[2]

(Ref. 2, Page 496)

C	0.04
Mn	0.18
Fe	18.5
S	0.008
Si	0.18
Cr	19.0
Ni	52.5
Mo	3.05
Cb	5.13
Ti	0.90
Al	0.50

Mechanical Properties

Modulus of Elasticity[2] (Ref. 2, Page 496)
= 29.8 x 10^6 psi (tension) = *205 GPa
= 11.6 x 10^6 psi (torsion) = *80 GPa

Poisson's Ratio[2] = 0.28 (Ref. 2, Page 496, Table 10.4 – 11)

(Ref. 2, Page 496)

Temperature K (°F)	Tensile Strength[2] x 10^3 psi (MPa)	Yield Strength[2], 0.2% offset x 10^3 psi (MPa)	Elongation[2], in 2 in. %
*294 (70)	208 *(1434)	172 *(1186)	21
*811 (1000)	185 *(1275)	154 *(1062)	18
*922 (1200)	178 *(1227)	148 *(1020)	19
*1033 (1400)	138 *(951)	107 *(737.7)	25
*1144 (1600)	49 *(338)	48 *(330.9)	88
*1255 (1800)	15 *(103)	15 *(103.4)	170
*1366 (2000)	8 *(55)	8 *(55.1)	125

Thermal Properties

Specific Heat[2] = 0.104 Btu/lb·°F at 70 °F = *435.2 J/kg·K at 294 K (Ref. 2, Page 496)

Thermal Conductivity[1] at 20 °C = 11.2 W/m·K at *293 K (20 °C)
(Ref. 1, Page 1276, Table 2.7.6)

Thermal Expansion[1] (20-95 °C) = 13 x 10^{-6}/K at *293-368 K (20-95 °C)
(Ref. 1, Page 1276, Table 2.7.6)

Coefficient of Thermal Expansion[2] (70-200 °F) = 7.2 x 10^{-6} in/in·°F (Ref. 2, Page 496)
*(294-366 K) = *12.96 x 10^{-6}/K

*Data converted to SI units[3]

---

1. Waterman, N. A.; Ashby, M. F. 1991. *CRC Elsevier Materials Selector*. Boca Raton, FL: CRC Press. TIC: 240578
2. Lynch, C. T. 1989. *Practical Handbook of Material Science*. Boca Raton, FL: CRC Press. TIC: 240577
3. American Society of Testing and Materials 1997. *Standard Practice for Use of the International System of Units (SI): The Modern Metric System*. ASTM Designation: ASTM SI 10-1997. West Conshohocken, PA: ASTM. TIC: 240989

5.32 Alumina 99%

Density[1,2,4] = 3650-3970 kg/m^3 (Ref. 1, Page 70, Table 2.3.1)

Porosity[1] = 1-8% (Ref. 1, Page 70, Table 2.3.1)

Thermal Properties

(Ref. 1, Page 75, Table 2.4.1)

Temperature K (°C)	Specific Heat[1] J/kg·K
*223 (-50)	540
*298 (25)	780
*373 (100)	920
*773 (500)	1160
*1273 (1000)	1250
*1773 (1500)	1320

(Ref. 1, Page 82, Table 2.4.3)

Temperature K (°C)	Thermal Expansion Coefficient[1], x 10^{-6}/K
*223 (-50)	4.5
*373 (100)	5.9
*773 (500)	7.4
*1273 (1000)	8.0
*1773 (1500)	9.0

(Ref. 1, Page 88, Table 2.4.6)

Temperature K (°C)	Thermal Conductivity[1] W/m·K
*223 (-50)	~50
*298 (25)	33
*373 (100)	29
*773 (500)	12
*1273 (1000)	9
*1773 (1500)	7

Emissivity[1] = 0.1-0.3 (Ref. 1, Page 182, Table 2.8.2)

Mechanical Properties

Elastic Moduli [1] = 380 GN/m^2 (Ref. 1, Page 95, Table 2.5.1)

Poisson Ratio[3] = 0.21-0.27 (Ref. 3, Page 398)

Tensile Strength[3] at 500 °C = 40 x 10^3 psi = *275.8 Mpa (Ref. 3, Page 871)

Crystal Structure[4]: Hexagonal (Ref. 4, Page 299, Table 6.2-1)

*Data converted to SI units[5]

---

1. Morrell, R. 1985. *Handbook of Properties of Technical and Engineering Ceramics - Part 1: An Introduction for the Engineer and Designer*. London, England: Her Majesty's Stationery Office. TIC: 240709
2. Clauss, F. J. 1969. *Engineer's Guide to High-Temperature Materials, Properties of Oxides (Table 8.1)*. Reading, MA: Addison-Wesley Publishing Company. TIC: 239825
3. Shackelford, J.; Alexander, W.; Park, J. 1995. *CRC Practical Handbook of Materials Selection*. Boca Raton, FL: CRC Press. TIC: 240579
4. Lynch, C. T. 1989. *Practical Handbook of Materials Science*. Boca Raton, FL: CRC Press. TIC: 240577
5. American Society of Testing and Materials 1997. *Standard Practice for Use of the International System of Units (SI): The Modern Metric System*. ASTM Designation: ASTM SI 10-1997. West Conshohockon, PA: ASTM. TIC: 240989

5.33 Spinel ($MgAl_2O_4$)

Density[1] = 2800-3580 kg/m^3 (theoretical) (Ref. 1, Page 70, Table 2.3.1)

Porosity[1] = 0-10% (Ref. 1, Page 70, Table 2.3.1)

Thermal Properties

(Ref. 1, Page 75, Table 2.4.1)

Temperature K (°C)	Specific Heat[1] J/kg·K
*223 (-50)	-
*298 (25)	810
*373 (100)	940
*773 (500)	1180
*1273 (1000)	1300
*1773 (1500)	1400

(Ref. 1, Page 82, Table 2.4.3)

Temperature K (°C)	Thermal Expansion Coefficient, x 10^{-6}/K
*223 (-50)	-
*373 (100)	5.6
*773 (500)	7.6
*1273 (1000)	8.4
*1773 (1500)	10.2

(Ref. 1, Page 88, Table 2.4.6)

Temperature K (°C)	Thermal Conductivity[1] W/m·K
*223 (-50)	-
*298 (25)	~15
*373 (100)	~13
*773 (500)	~8
*1273 (1000)	~5
*1773 (1500)	-

Mechanical Properties

Elastic Moduli[1] = 260-328 GN/m^2 (Ref. 1, Page 95, Table 2.5.1)

Tensile Strength[2] (Ref. 2, Page 368-369)
at 550 °C = 13.7 x 10^3 psi = 94.5 MPa
at 1150 °C = 6.1 x 10^3 psi = 42.1 MPa

*Data converted to SI units[3]

---

1. Morell, R. 1985. *Handbook of Properties of Technical and Engineering Ceramics - Part 1: An Introduction for the Engineer and Designer*. London, England: Her Majesty's Stationery Office. TIC: 240709
2. Shackelford, J.; Alexander, W.; Park, J. 1995. *CRC Practical Handbook of Materials Selection*. Boca Raton, FL: CRC Press. TIC: 240579
3. American Society of Testing and Materials 1997. *Standard Practice for Use of the International System of Units (SI): The Modern Metric System*. ASTM Designation: ASTM SI 10-1997. West Conshohocken, PA: ASTM. TIC: 240989

5.34 Titania C 310 (Rutile)

Density[1,2] = 3500-4000 kg/m^3 (Ref. 2, Page 70, Table 2.3.1)

Porosity[2] = 2-8% (Ref. 2, Page 70, Table 2.3.1)

Thermal Properties

Thermal Conductivity (Ref. 1, Page 458, Table 1)
at room temperature[1] = 0.016 cal/s/cm·°C = *6.7 W/m·K
at 1000 °C[1] = 0.008 cal/s/cm·°C = *3.3 W/m·K

(Ref. 2, Page 75, Table 2.4.1)

Temperature K (°C)	Specific Heat[2] J/kg·K
*223 (-50)	570
*298 (25)	690
*373 (100)	780
*773 (500)	910
*1273 (1000)	940
*1773 (1500)	960

(Ref. 2, Page 82, Table 2.4.3)

Temperature K (°C)	Thermal Expansion Coefficient[2,3], x 10^{-6}/K
*223 (-50)	-
*373 (100)	5-7
*773 (500)	7-8
*1273 (1000)	8-9
*1773 (1500)	-

Mechanical Properties

Elastic Moduli[2] = 90-140 GN/m^2 (Ref. 2, Page 95, Table 2.5.1)

*Data converted to SI units[4]

1. Riley, M. 1963. *The Encyclopedia of Engineering Materials and Processes.* New York, NY: Reinhold Publishing Corporation. TIC: 243221

2. Morrell, R. 1985. *Handbook of Properties of Technical and Engineering Ceramics - Part 1: An Introduction for the Engineer and Designer*. London, England: Her Majesty's Stationery Office. TIC: 240709
3. Shackelford, J.; Alexander, W.; Park, J. 1995. *CRC Practical Handbook of Materials Selection*. Boca Raton, FL: CRC Press. TIC: 240579
4. American Society of Testing and Materials 1997. *Standard Practice for Use of the International System of Units (SI): The Modern Metric System*. ASTM Designation: ASTM SI 10-1997. West Conshohocken, PA: ASTM. TIC: 240989

5.35 Zirconia (ZrO_2)

Density[1,3] = 6100 kg/m^3 (Ref. 1, Page 221, Table 8.1)

Thermal Properties

Emissivity[3] = 0.1-0.3 (Ref. 3, Page 182, Table 2.8.2)

Coefficient of Thermal Expansion[1] = 8.7x10^{-6} cm/cm·°C (Ref. 1, Page 221, Table 8.1)

(Ref. 3, Page 75, Table)

Temperature K (°C)	Specific Heat[3] J/kg·K
*223 (-50)	380
*298 (25)	450
*373 (100)	510
*773 (500)	590
*1273 (1000)	640
*1773 (1500)	600

(Ref. 3, Page 82, Table 2.4.3)

Temperature K (°C)	Thermal Expansion Coefficient[3] (Partially Stabilized Zirconia) x 10^{-6}/K
*373 (100)	7-8
*773 (500)	8-9
*1273 (1000)	9-10
*1773 (1500)	-

(Ref. 3, Page 88, Table 2.4.6)

Temperature K (°C)	Thermal Conductivity[3] (Partially Stabilized Zirconia) W/m·K
*298 (25)	1.3
*373 (100)	1.3
*773 (500)	1.4
*1273 (1000)	1.5

Thermal Conductivity[2] (plasma sprayed) (Ref. 2, Page 322)
= 0.0019-0.0031 cal/s/cm·K at RT
= 0.0019-0.0022 cal/s/cm·K at 800 °C

Mechanical Properties

Elastic Moduli[3] = 100 GN/m^2 (Ref. 3, Page 95, Table 2.5.1)

Poisson's Ratio[2] = 0.23 (Ref. 2, Page 398)

Modulus of Elasticity[1] = 25x10^6 psi = *172 GPa (Ref. 1, Page 221, Table 8.1)

Compressive Strength[1] = 303,000 psi = *2.1 GPa (Ref. 1, Page 221, Table 8.1)

Data converted to SI units[4]

---

1. Clauss, F. J. 1969. *Engineer's Guide to High-Temperature Materials, Properties of Oxides (Table 8.1)*. Reading, MA: Addison-Wesley Publishing Company. TIC: 231761
2. Shackelford, J.; Alexander, W.; Park, J. 1995. *CRC Practical Handbook of Materials Selection*. Boca Raton, FL: CRC Press. TIC: 240579
3. Morrell, R. 1985. *Handbook of Properties of Technical and Engineering Ceramics - Part 1: An Introduction for the Engineer and Designer*. London, England: Her Majesty's Stationery Office. TIC: 240709
4. American Society of Testing and Materials 1997. *Standard Practice for Use of the International System of Units (SI): The Modern Metric System*. ASTM Designation: ASTM SI 10-1997. West Conshohocken, PA: ASTM. TIC: 240989

6. Results

None

7. References

References are to be found at the end of each subsection in Section 5.

8. Attachments

None