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Review Copy

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SUBJECT: A COMPILATION OF ROOM TEMPERATURE AND 1200° F PROPERTIES OF METALLIC MATERIALS WITH SPECIFIC REFERENCE TO THEIR USE AS FUEL CLADDING IN SODIUM COOLED THERMAL REACTORS

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IV REFERENCES AND APPENDICES . . . . . PAGE

I STATEMENT OF PROBLEM

It is the purpose of this TDR to present a compilation of room temperature and 1200° F properties of a large number of alloys which might be considered for use in a sodium cooled reactor. Specific consideration is given to the use of such materials as fuel cladding. The arbitrary basis for property comparison is stainless type 304.

DISCUSSION

Table I lists the nominal compositions of the materials studied. This table is divided into ten classes as noted. Each class lists at least one alloy which can be considered typical in a general sense for that class of material.

Class 1 lists a moderately alloyed ferritic steel which is widely used in the petroleum and power industries. The alloying elements Cr and Mo are added primarily for improved oxidation resistance, elevated temperature strength and resistance to graphitization. The use of this alloy as a fuel cladding material in 1200° F sodium is unlikely due to --

(1) Lower 1200° F creep and stress rupture properties than 304.

(2) Tendency to decarburization in 1200° F sodium.

* (3) Where uranium base alloy fuels are used the maximum temperature of the fuel/cladding interface is limited by the U-Fe eutectic temperature of 1350-1400° F.

(4) Tendency to present welding problems due to air hardening of moderate to thin sections. This would be important from the standpoint of possible weld cracking of end caps unless proper pre-and post- heat precautions were taken.

The alloy 481 listed in this class is presently under development by the Materials Development Group. Its composition is basically the 2¼ Cr-1 Mo alloy with additions of strong carbide forming elements. The purpose of designing such a composition is to attempt to overcome the first two previously mentioned disadvantages. Test results to date have shown the alloy to be superior to the 2¼ Cr - 1 Mo in these areas, i.e., resistance to decarburization in 1200° F sodium and higher 1200° F strength and creep-rupture properties.

The ferritic stainless steels of Class 2 generally suffer from the same disadvantages as the 2¼ Cr - 1 Mo alloy. Of the four alloys listed, Type 410 is the only one which is hardenable by heat treatment. All of these alloys have lower 1200° F creep and stress to rupture properties than either 304 or the 2¼ Cr - 1 Mo alloy. The resistance of these materials to 1200° F sodium is better than the 2¼ Cr - 1 Mo.

The Class 3 materials are also ferritic materials. Armco iron is listed primarily for comparison purposes and its reportedly high resistance to 1200° F sodium. The two alloys "Thermenol" and "Alfenol 16" were developed primarily for oxidation resistance at temperatures in the region of 1800° F.

Their strength characteristics are reported to be dependent upon an ordered structure and low impurity content. The former requires relatively complex thermal treatment, while the latter necessitates melting in either vacuum or a purified inert atmosphere. Limited 1200° F stress rupture data show the thermenol alloy to be

* This applies to any of the iron, nickel, or cobalt base alloys.

superior to the chromium bearing ferritic stainless steels to times of 1000 hours. Beyond this time, this property decreases markedly suggesting microstructural instability. No creep data are readily available, but the specimen from the aforementioned stress-rupture test exhibited an elongation of 233% in 3/4" under a stress of 10,000 psi. The time to rupture was 796 hours. No information is available on the resistance of these iron-aluminum alloys to 1200° F sodium. The primary advantage of these materials is their lower absorption cross section for thermal neutrons when compared with 304 stainless steel. At the present time, these alloys are still in the development stage, and are not readily available.

The Class 4 materials typify the austenitic stainless steels which are most commonly used. They have, at 1200° F, superior creep and stress rupture properties than do the ferritic materials. Their resistance to 1200° F sodium is good. Where carbon is available they have a strong tendency to carburize at 1200° F which increases the yield and tensile strengths and lowers the ductility at both room and elevated temperatures. The effect of carburization of these materials on their creep and stress rupture properties is somewhat complex since the measurement of these properties requires long time periods at elevated temperatures under constant load. Consequently diffusion of carbon will be occurring in the carburized specimen during test. This problem of carburization becomes important where the fuel is hyperstoichiometric UC or where carbon is available for transfer by the sodium coolant. Perhaps the major disadvantage of this class of alloys is their high absorption cross section for thermal neutrons.

The two alloys listed in Class 5 are typical of the present commercially available precipitation hardening stainless steels. They were developed primarily for high strength properties and oxidation resistance at temperatures to 1000° F. There are very few data available beyond this temperature. For 1200° F operation, the standard austenitic stainless steels would be superior.

With the exception of pure nickel, the alloys listed in Class 6 (ferrous base), 7 (nickel base), and 8 (cobalt base) were developed for applications in the temperature range of about 1200° to 1800° F where the strength requirements were excessive for the standard austenitic stainless steels. Their use as cladding materials for metal fuels would be limited by:

(1) U-Fe, U-Ni, and U-Co eutectics of respectively 1340°, 1365°, and 1375° F.

(2) High absorption cross sections of the nickel and cobalt base alloys when compared with 304 stainless.

(3) Post exposure handling problems for the cobalt base or cobalt containing alloys.

According to the Liquid Metals Handbook, all of these alloys would be expected to provide good resistance to 1200° F sodium. Where UC is considered as the fuel and where the elevated temperature strength properties of the standard austenitic stainless steels are inadequate, serious consideration should be given such materials as A-286, 19-9 DL, Inconel X, Hastelloy B, and Hastelloy R-235. However, carburizing tendencies of these materials by either hyperstoichiometric UC or the coolant requires investigation.

Copper and its alloys (Class 9) are eliminated for use in sodium cooled reactors on the basis of:

(1) Inadequate resistance to the coolant.

(2) Poor elevated temperature strength.

Of the Class 10 materials, zirconium and columbium and their alloys as well as beryllium are highly attractive for thermal reactor use because of their low cross sections. Molybdenum has excellent high temperature strength properties but is open to some question on the basis of absorption cross section -- especially in the epi-thermal region.

The properties of all of these materials are influenced (usually deleteriously) by the presence of small amounts of interstitials (e.g., C, N, O, H).

Where metallic uranium or its alloys are concerned, none of the refractory metals form low melting eutectics (the lowest reported is ~1900° F for the U-V system).

Since all of these materials form stable carbides, their behavior with UC fuels at elevated temperatures requires considerable investigation.

With the exception of Ti, all of the materials listed are reported to have good resistance to 1200° F sodium.

The creep and stress-rupture properties of zirconium and its alloys are inferior to 304 stainless steel at 1200° F. Alloy 3Z1 most closely approaches the elevated temperature strength properties of 304.

The major disadvantages of these refractory metals and alloys are:

(1) Their limited availability

(2) Their high cost

Both of these disadvantages are due primarily to the following: (1) they are in relatively early stages of development, and (2) they require protection from atmospheric contamination during fabrication or processing at elevated temperatures -- e.g., melting, heat treating, and welding must be done in either vacuum or inert atmosphere.

Physical properties for the 10 classes of materials are tabulated in Tables 2-11, pp 9-19. These tables include: macroscopic absorption cross-section, thermal conductivity, thermal expansion, density and melting point or range for each of the materials.

In Tables 12-21, the tensile properties of the materials are shown for 80° and 1200° F. Typical properties described include: Yield Strength @ 0.2% Offset, Ultimate Tensile Strength, Elongation and Modulus of Elasticity.

Tables 22-28, contain 1200° F creep and stress-rupture properties for many of the materials. For some of the alloys, this information was not available at or close to 1200° F. For others, the temperature of interest is at a level where the material would be unable to sustain a useful load.

The properties for Type 304, Stainless Steel were added to each table for comparative purposes. In Tables 12-21, the tensile properties for this material represent typical values. The maximum allowable stresses used for design would be somewhat lower than the properties described.

TABLE 1 - NOMINAL COMPOSITIONS

Class & Alloy	C (Max)	Cr	Ni	Co	Ti	Al	Fe	Mo	Mn	Other	Reference
Class 1, Alloy Steels											
2¼ Cr-1 Mo	0.15	2.25					Bal	1			
4S1	0.15	2.25			0.4			1		0.4 Cb	
Class 2, Ferritic Stainless Steels											
Type 410	0.15	12.5					Bal				21
Type 430	0.12	16					Bal				21
Type 446	0.35	25					Bal				21
Type 406	0.15	13				4	Bal				21
Class 3, Iron & Iron-Aluminum Alloys											
Armco Ingot Iron	0.01								0.02	P 0.005, S 0.025, Si Trace (Typical)	21
Thermenol	0.05					15.5	Bal	3.5			14
Alfenol 16	0.01					16	Bal				14
Class 4, Austenitic Stainless Steels											
Type 304	0.08	19	9.5				Bal		2		21
Type 316	0.10	17	12				Bal	2.5			21
Type 347	0.08	18	10.5				Bal			Cb 10 XC	21
321	0.08	18	10				Bal		2	Ti 5 XC Min.	
Class 5, Precipitation Hardening Stainless Steels											
17-7 PH	0.09	17	7			1.5	Bal		1.00	1.00 Si	23
AM 350	0.12	16.5	4.5				Bal	3	0.90	0.10 N, 0.5 Max Si	23

Table 1 - Cont --

Class & Alloy	C (Max)	Cr	Ni	Co	Ti	Al	Fe	Mo	Mn	Other	Reference
Class 6, Austenitic Super Alloys (Iron Base)											
A-286	0.08	15	25		1.9	0.35	Bal	1.25		0.25 V	14
19-9 DL	0.30	19	9		0.30		Bal	1.25		0.40 Cb, 1.25 W	14
N-155	0.15	20	20	20			Bal	3		1 Cb, 0.15 N, 2.5 W	14
Class 7, Nickel Base Alloys											
Nickel			100								
Inconel X	0.04	15	73		2.4	0.6	7.0			1 Cb	14
Hastelloy B	0.10		64				6	28			14
Hastelloy R 235	0.10	15.5	67		2.5	2.25	7	5			14
Udimet 500	0.10	16	52	19	3	3	2	4		,0.005 B, 0.06 Zr	14
Hastelloy N	0.08	6.00-8.00			Al+Ti= 0.5max		5.00 max	15.00-18.00	0.8Max	0.01B max, 0.03S Max, 0.5 Si Max,	(33)
Class 8, Cobalt Base Alloys											
S-816	0.40	20	20	44			Bal	4		4 Cb, 4 W	14
Haynes 25	0.15	20	10	Bal			2		1.5	15 W, 1.0 Max Si	22
Class 9, Copper Base Alloys											
Copper										100 T Cu	
Beryllium Copper			0.35 or 0.35							2 Be, Bal Cu	21
Cartridge Brass										70 Cu, 30 Zn	21
Class 10, Refractory Metals & Alloys											
Molybdenum								100			
Moly-½% Ti					0.5			99.5			
Zirconium										100%Zr	
Zircaloy-2										1.5 Sn, Cr + Fe + Ni, Bal Zr, from 0.18 to 0.38, Bal Zr	18
AI 3Z1						1.25		1.0		1.0 Sn, Bal Zr	
Tungsten										100% W	

Table 1 - Cont --

Class & Alloy	C (Max)	Cr	Ni	Co	Ti	Al	Fe	Mo	Mn	Other	Reference
Class 10, Refractory Metals & Alloys											
Tantalum										100% Ta	
Columbium										100% Cb	
Vanadium										100% V	
Titanium					100						
Beryllium										100% Be	
Cb-1 Zr										1.0 Zr, Bal Cb	

TABLE 2. CLASS 1. ALLOY STEELS

Nominal Composition

Alloy Steels	2.25% Cr	1% Mo and 4Si
Type 304*	0.08% C, 19% Cr, 9.5% Ni, 2% Mn	

Physical Properties

	Alloy Steel	Type 304
Macroscopic Absorption Cross Section, Cm^{-1}	0.22 (19)	0.26 (19)
Thermal Conductivity, BTU/hr-ft-°F	15.8 (13) Est. nearly constant	7.35 at 70° (14) 14.1 at 1200° (14)
Thermal Expansion, μ in/in-°F	8.1 70°-1200° (13)**	8.7 70°-200° (14) 10.7 70°-1500° (14)
Density, g/cc	7.87 (19)	7.94 (14)
Melting Point or Melting Range, °F	2775-2825 Est.	2550-2650 (14)

* For comparison

** Converted

TABLE 3, CLASS 2, FERRITIC STAINLESS STEELS

Nominal Compositions (Ref. 21)

Type	% C	% Cr	% Ni	% Other
410	0.15	12.5		
430	0.12	16		
446	0.35	25		
406	0.15	13		4 Al
304*	0.08	19	9.5	2 Mn

Physical Properties

Type	Macroscopic Absorption Cross Section, Cm^{-1}	Thermal Conductivity BTU/hr-ft-°F	Thermal Expansion μ in/in-°F	Density g/cc	Melting Point or range °F
410	Σ = 0.22 (19)	13.4 at 200° F (21)	7.0 0°-1500°F (21)	7.75 (21)	2700-2750 (21)
		15.3 at 1000° F			
430	0.22 (19)	13 at 200° F (21)	6.3 0°-1500°F (21)	7.70 (21)	2650-2700 (21)
		14.2 at 1000° F			
446	0.22 (19)	11.6 at 200° F (21)	6.2 0°-1500°F (21)	7.60 (21)	2550-2750 (21)
		13.5 at 1000° F			
406	0.20 (19)	7.5 Est. at 68°	7.9 32°-1500° (24)	7.32** (24)	2650-2750 Est.
304*	0.26 (19)	7.35 at 70° F (14)	8.7 70°-200°F (14)	7.94 (14)	2550-2650 (14)
		14.1 at 1200° F	10.7 70°-1500° F		

*For comparison

** Converted

TABLE 4, CLASS 3, IRON AND IRON-ALUMINUM ALLOYS

Nominal Composition

	% C	% Cr	% Al	% Ni	% Mo	% Mn	% P	% S	Si	
Armco Ingot Iron	0.01					0.02	0.005	0.025	Trace	(21)
Thermenol	0.05		15.5		3.3					(14)
Alfenol 16	0.01		16							(14)
Type 304 SS*	0.08	19		9.5		2.0				

Physical Properties

Alloy	Macroscopic Absorption Cross Section, Cm^{-1}	Thermal Conductivity BTU/hr-ft-°F	Thermal Expansion μ in/in-°F	Density g/cc	Melting Point or Range, °F
Armco Ingot Iron	0.21 (19)	39.8 ~212° (21)	7.0** at 212° (21)	7.86 (21)	2802** (21)
Thermenol	0.14 (19)	5.4 Est. ~68°	8 at 68° Est.	6.08 (19)	2650-2750 Est.
Alfenol 16	0.14 (19)	5.4 Est. ~68°	8 at 68° Est.	6.02 (19)	2650-2800 Est.
Type 304	0.26 (19)	7.35 at 70°, 14.1 at 1200° (14)	8.7 79°-200° (14) 10.7 70°-1500° (14)	7.94 (14)	2550-2650 (14)

*For comparison

** Converted

TABLE 5, CLASS 4, AUSTENITIC STAINLESS STEELS

Nominal Composition (Ref. 21)

Alloy	% C	% Cr	% Ni	% Mn	% Mo	Other
Type 304	0.08	19	9.5	2		
Type 316	0.10	17	12		2.5	
Type 347	0.08	18	10.5			Cb 10XC
Type 321	0.08	18	9.5			Ti 5XC min

Physical Properties

Alloy	Macroscopic Absorption Cross Section, Cm^{-1}	Thermal Conductivity BTU/hr-ft-°F	Thermal Expansion μ in/in-°F	Density g/cc	Melting Point or Range, °F
Type 304	0.26 (19)	7.35 at 70° (14)	8.7 70°-200° (14)	7.94 (14)	2550-2650 (14)
		14.1 at 1200° (14)	10.7 70°01500° (14)		
Type 316	0.24 (19)	9.0 at 200° (21)	11 0°-1500° (21)	7.98 (21)	2500-2550 (21)
		12.25 at 1000° (21)			
Type 347	0.24 (19)	9.25 at 212° (21)*	10.6 0°-1200° (21)	8.03 (21)*	2550-2600 (21)
		12.8 at 932° (21)*			
Type 321	0.26 (19)	12.5 at 1000° (21)	11.3 0°-1500° (21)	8.02	2550-2600 (21)

* Converted

TABLE 6, CLASS 5, PRECIPITATION HARDENING STAINLESS STEELS

Nominal Composition

Alloy	% C	% Cr	% Ni	% Others
17-7 PH	0.09	17	7	1.15 Al, 1.0 Mn, 1.0 Si (23)
AM-350	0.12	16.5	4.5	3.0 Mo, 0.1 N, 0.5 Si, 0.9 Mn (23)
Type 304*	0.08	19	9.5	2 Mn (21)

Physical Properties

Alloy	Macroscopic Absorption Cross Section, Cm^{-1}	Thermal Conductivity BTU/hr-ft-°F	Thermal Expansion μin/in-°F	Density g/cc	Melting Point or Range, °F
17-7 PH	0.23 (19)	9.35 at 200° (1)	6.1 70°-800° (1)	7.67** (1)	2550°-2650 Est
		12.0 at 800° (1)			
AM-350	0.24 (19)	12.4 at 932° Est.	6.7 70°-1400° (1)	7.94** (1)	2550-2650 Est.
Type 304*	0.26 (19)	7.35 at 70° (14)	8.7 70°-200° (14)	7.94 (14)	2550-2650 (14)
		14.1 at 1200° (14)	10.7 70°-1500° (14)		

*For comparison

**Converted

TABLE 7. CLASS 6. AUSTENITIC SUPER ALLOYS

Nominal Composition

Alloy	% C	% Cr	% Ni	% Co	% Ti	% Al	% Mo	% Others	
A-286	0.08	15	25		1.9	0.35	1.25	0.25 V	(14)
19-9 DL	0.30	19	9		0.30		1.25	0.4 Cb, 1.25 W	(14)
N-155	0.15	20	20	20			3	1 Cb, 0.15 N, 2.5 W	(14)
Type 304 SS*	0.08	19	9.5					2 Mn	(21)

Physical Properties

Alloy	Macroscopic Absorption Cross Section, Cm^{-1}	Thermal Conductivity BTU/hr-ft-°F	Thermal Expansion μin/in-°F	Density g/cc	Melting Point or Range, °F
A-286	0.27 (19)	7.35 at 70° (14)	9.2 70°-200° (14)	7.94 (14)	2500-2600(14)
		14.35 at 1200° (14)	10.3 70°-1500° (14)		
19-9 DL	0.24 (19)	7.84 at 70° (14)	8.5 70°-200° (14)	7.94 (14)	2590-2615 (14)
		12.25 at 1200° (14)	10 70°-1500° (14)		
N-155	0.85 (19)	7.1 at 70° (14)	8.7 70°-600° (14)	8.27 (14)	2325-2475 (14)
		12.8 at 1200° (14)	9.8 70°-1500° (14)		
Type 304*	0.26 (19)	7.35 at 70° (14)	8.7 70°-200° (14)	7.94 (14)	2550-2650 (14)
		14.1 at 1200° (14)	10.7 70°-1500° (14)		

*For comparison

TABLE 8. CLASS 7. NICKEL BASE ALLOYS

Nominal Composition

Alloy	% C	% Cr	% Ni	% Ti	% Al	% Fe	% Mo	% Others	
Nickel			100						
Inconel X	0.04	15	73	2.4	0.60	7.0		1 Cb	(14)
Hastelloy B	0.10		64			6	28		(14)
Hastelloy R-235	0.10	15.5	67	2.5	2.25	7	5		(14)
Udimet 500	0.10	16	52	3	3	2	4	19 Co, 0.005B, 0.06 Zr	(14)
Type 304 SS*	0.08	19	9.5			Bal		2 Mn	(21)
Hastelloy N	0.08	6.00-8.00		Al+Ti= 0.5max		5.00max	15.00-18.00	0.01B max, 0.03 S max, 0.5 Si, max 0.8 Mn max	(33)

Physical Properties

Alloy	Macroscopic Absorption Cross Section, Cm^{-1}	Thermal Conductivity BTU/hr-ft-°F	Thermal Expansion μin/in-°F	Density g/cc	Melting Point or Range, °F
Nickel	0.42 (19)	53.4 at 68° (21)	7.4 at 68° (21)	8.90 (21)	2651 (21)
Inconel X	0.36 (19)	7.1 at 68° (1)	7.6 at 100°-200° (1)	8.24** (1)	2540 (1)
		13.0 at 1200° (1)	8.4 100°-1200° (1)		
Hastelloy B	0.34 (19)	9.48 at 1112° (22)	6.73 70°-1200° (22)	9.24 (22)	2410 (21)
Hastelloy R-235	0.36 (19)	12.1 at 1200° (5)	8.1 200°-1200° (5)	8.30** (5)	2350-2450 (5)
Udimet 500	0.86 (19)	6.34 at 70° (14)	6.25 70°-200° (14)	8.02 (14)	2350-2450 (14)
		11.8 at 1200° (14)	8.36 70°-1500° (14)		
Type 304 SS*	0.26 (19)	7.35 at 70° (14)	8.7 70°-200° (14)	7.94 (14)	2550-2650 (14)
		14.1 at 1200° (14)	10.7 70°-1500° (14)		
Hastelloy N	0.356(19)	5.55 at 212°F(33) 16.2 at 1112°F(33) 18.1 at 1292°F(33)	5.76 70-400°F(33) 7.34 70°-1200°F(33) 8.10 70°-1600°F(33)	8.79(33)	2370-2430(33)

*For comparison
** Converted

TABLE 9, CLASS 8, COBALT BASE ALLOYS

Nominal Composition

Alloy	% C	% Cr	% Ni	% Co	% Fe	% Other
S-816	0.40	20	20	44	Bal	4 Mo, 4 Cb, 4 W (14)
Haynes 25	0.15	20	10	Bal	2	1.5 Mn, 15 W, 1 Max Si (22)
Type 304 SS*	0.08	19	9.5		Bal	2 Mn (21)

Physical Properties

Alloy	Macroscopic Absorption Cross Section, Cm^{-1}	Thermal Conductivity BTU/hr-ft-°F	Thermal Expansion μin/in-°F	Density g/cc	Melting Point or Range, °F
S-816	1.62 (19)	7.16 at 70° (14)	6.5 70°-200° (14)	8.66 (14)	2350-2450 (14)
		13.4 at 1200° (14)	7.8 70°-1500° (14)		
Haynes 25	1.99 (19)	12.5 at 1200° (5)	8.55 70°-1200° (5)	9.15 (5)	2570 (5)
Type 304*	0.26 (19)	7.35 at 70° (14)	8.7 70°-200° (14)	7.94 (14)	2550-2650 (14)
		14.1 at 1200° (14)	10.7 70°-1500° (14)		

*For comparison

TABLE 10, CLASS 9, COPPER BASE ALLOYS

Nominal Composition

Alloy	% Cr	% Ni	% Cu	% Fe	% Mn	% Other
Copper			100			
Beryllium Copper			Bal			0.35 Ni or 0.35 Cr, 2 Be
Cartridge Brass			70			30 Zn
Type 304 SS*	19	9.5		Bal	2	0.08 C Max

Physical Properties

Alloy	Macroscopic Absorption Cross Section, Cm^{-1}	Thermal Conductivity BTU/hr-ft-°F	Thermal Expansion μin/in-°F	Density g/cc	Melting Point or Range, °F
Copper	0.35 (19)	226.5* at 68° (21)	9.2 at 68° (21)	8.96 (21)	1981 (21)
Beryllium Copper	0.29 (19)	48.3* at 68° (21)	10.6 392°-572°** (21)	8.23 (21)	1587 (21)
Cartridge Brass	0.23 (19)	70.0* at 68° (21)	11.1 77°-572° (21)	8.53 (21)	1750 (21)
Type 304*	0.26 (19)	7.35 at 70° (14)	8.7 70°-200° (14)	7.94 (14)	2550-2650 (14)
		14.1 at 1200° (14)	10.7 70°-1500° (14)		

*For comparison
** Converted

TABLE 11, CLASS 10, REFRACTORY METALS AND ALLOYS

Nominal Composition

Alloy:

Molybdenum	Pure
Molybdenum - 1/2% Titanium	
Zirconium	Pure
Zircaloy-2	Sn 1.2 - 1.7%, Fe + Cr + Ni 0.18 - 0.38%, Zr Bal (18)
AI 3Zl	1.25 Al, 1 Mo, 1 Sn, Bal Zr
Tungsten	Pure
Tantalum	Pure
Columbium*	Pure
Vanadium	Pure
Titanium	Pure
Beryllium	Pure
Type 304 SS**	0.08% C, 19% Cr, 9.5% Ni, 2% Mn, Bal Fe (21)
Cb-1 Zr	1.0 Zr, Bal Cb

Physical Properties

(See next page)

*Niobium

** For comparison

(Table 11, Class 10 - Continued)

Physical Properties

Alloy	Macroscopic Absorption Cross-Section, Cm^{-1}	Thermal Conductivity BTU/hr-ft-°F	Thermal Expansion μin/in-°F	Density g/cc	Melting Point or Range, °F
Molybdenum	0.16 (19)	84.7 at 68° (21)	2.7 near 68° (21)	10.2 (21)	4760 (21)
Moly-½ Ti	0.16 (19)	7.5 at 68° (Est.)	3.13 32°-1400° (1)	10.17 (19)	4720 (21)
Zirconium	0.008 (19)	12.15 at 68° (26)	3 near 68° (21)	6.5 (21)	3364 (20)
Zircaloy-2	0.008 (19)	10.0 at 1100° (26)	3 near 68° (Est.)	6.53 (19)	3300 (Est.)
AI 3Zl	0.009 (19)	10.0 at 1100° (Est.)	3 near 68° (Est.)	6.46 (19)	3300 (Est.)
Tungsten	1.21 (19)	116 at 68° (21)	2.4 near 68° (21)	19.3 (21)	6170 (21)
Tantalum	1.18 (19)	31.4 at 68° (21)	3.6 near 68° (21)	16.6 (21)	5425 (21)
Columbium*	0.06 (19)	33.8 at 1112° (2)	4.0 near 68° (21)	8.57 (21)	4380 (21)
Vanadium	0.36 (19)	21.2 at 932° (3)	4.3 near 68° (21)	6.0 (21)	3150 (21)
Titanium	0.32 (19)	8.1 at 212° (27)	4.7 near 68° (21)	4.54 (21)	3300 (21)
Beryllium	0.001 (19)	65 at 1200° (6)	8.7 near 68 1292° (6-conv.)	1.86 (6-conv)	2345 (6)
Type 304 SS**	0.26 (19)	7.35 at 70° (14) 14.1 at 1200° (14)	8.7 70°-200° (14) 10.7 70°-1500° (14)	7.94 (14)	2550-2650 (14)
Cb-1 Zr	0.0605 (19)			8.55 (19)	

*Niobium
** For comparison

TABLE 12, CLASS 1, ALLOY STEEL

TENSILE PROPERTIES

TYPE OF MATERIAL	0.2% OFFSET YIELD STRENGTH (PSI)		ULTIMATE TENSILE STRENGTH (PSI)		ELONGATION % IN 2"		MODULUS OF ELASTICITY (10^6 PSI)		REFERENCE
	80° F	1200° F	80° F	1200° F	80° F	1200° F	80° F	1200° F	
Steel 2% Cr + 1 Mo	43,000	20,000	72,000	32,000	43	54	-	-	13
Type 304 Stainless Steel	34,000	12,000	85,000	42,000	63	39	28.3	21.5	13
481*	103,800	56,000	116,600	60,000	16**	18	-	-	32

*For material normalized at 2150° F and tempered at 1200° F - 1 hr

** Elongation in 1"

TABLE 13, CLASS 2, FERRITIC STAINLESS STEELS

TENSILE PROPERTIES

TYPE OF MATERIAL	0.2% OFFSET YIELD STRENGTH (PSI)		ULTIMATE TENSILE STRENGTH (PSI)		ELONGATION % IN 2"		MODULUS OF ELASTICITY (10^6 PSI)		REF.
	80° F	1200° F	80° F	1200° F	80° F	1200° F	80° F	1200° F	
410	-	-	89,000	23,000	30	50	29	-	13
430	39,500	12,000	74,000	22,000	32	55	29	-	13
446	51,500	13,000	83,000	24,000	25	60	29	-	13
406	-	-	86,000	20,500	25	61	29	-	24
Type 304 Stainless Steel	34,000	12,000	85,000	42,000	63	39	28.3	21.5	13

TABLE 14, CLASS 3 IRON AND IRON-ALUMINUM ALLOYS

TYPE OF MATERIAL	0.2% OFFSET YIELD STRENGTH (PSI)		ULTIMATE TENSILE STRENGTH (PSI)		ELONGATION % IN 2"		MODULUS OF ELASTICITY (10^6 PSI)		REF.
	80° F	1200° F	80° F	1200° F	80° F	1200° F	80° F	1200° F	
Armco Iron	33,700	7,000	46,300	8,800	31.0	26.5	29.8	-	30,21
Thermenol	71,000*	-	90,000*	53,000**	3.7*	16.6**	-	-	31
Alfenol 16	65,000	-	85,000	-	24	-	-	-	31
Type 304 Stainless Steel	34,000	12,000	85,000	42,000	63	39	28.3	21.5	13

* Rolled bar, annealed at 1925° F
** Hot rolled plate

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TABLE 15, CLASS 4, AUSTENITIC STAINLESS STEELS

TENSILE PROPERTIES

TYPE OF MATERIAL	0.2% OFFSET YIELD STRENGTH (PSI)		ULTIMATE TENSILE STRENGTH (PSI)		ELONGATION % IN 2"		MODULUS OF ELASTICITY (10^6 PSI)		REF.
	80° F	1200° F	80° F	1200° F	80° F	1200° F	80° F	1200° F	
304	34,000	12,000	85,000	42,000	63	39	28.3	21.5	13
316	38,500	20,000	85,500	59,000	60	42	-	-	13
347	39,500	26,000	91,000	48,000	50	45	-	-	13
321	33,000	17,700	85,000	43,000	58	49.5	-	-	13

TABLE 16 CLASS 5, PRECIPITATION HARDENING STAINLESS STEELS

TENSILE PROPERTIES

TYPE OF MATERIAL	0.2% OFFSET YIELD STRENGTH (PSI)		ULTIMATE TENSILE STRENGTH (PSI)		ELONGATION % IN 2"		MODULUS OF ELASTICITY (10^6 PSI)		REF.
	80° F	1200° F	80° F	1200° F	80° F	1200° F	80° F	1200° F	
17-7 PH-TH 1050	150,000	--	180,000	--	11.5	--	29	--	1
AM 350- SCT	152,000	47,000	198,000	68,000	13	16	--	--	1
Type 304 Stainless Steel	34,000	12,000	85,000	42,000	63	39	28.3	21.5	13

TABLE 17 CLASS 6, AUSTENITIC SUPER ALLOYS (IRON BASE)

TENSILE PROPERTIES

TYPE OF MATERIALS	0.2% OFFSET YIELD STRENGTH (PSI)		ULTIMATE TENSILE STRENGTH (PSI)		ELONGATION % IN 2"		MODULUS OF ELASTICITY (10^6 PSI)		REF.
	80° F	1200° F	80° F	1200°F	80° F	1200° F	80° F	1200° F	
A-286	93,500	86,000	143,500	103,000	24	13	29	21	14
19-9 DL	69,000	37,000	118,300	75,000	55.5	33.5	29.5	21.5	14
N-155	57,000	43,000	119,000	80,000	43	31	29.3	22	14
Type 304 Stainless Steel	34,000	12,000	85,000	42,000	63	39	28.3	21.5	13

TABLE 18 CLASS 7, NICKEL BASE ALLOYS

TENSILE PROPERTIES

TYPE OF MATERIAL	0.2% OFFSET YIELD STRENGTH (PSI)		ULTIMATE TENSILE STRENGTH (PSI)		ELONGATION % IN 2"		MODULUS OF ELASTICITY (10^6 PSI)		REF.
	80° F	1200° F	80° F	1200° F	80° F	1200° F	80° F	1200° F	
Nickel	22,000	10,000	65,000	23,000	50	--	--	--	15
Inconel X	132,000	100,000	184,000	142,000	24	12	31.5	25	1
Hastelloy B	55,000	--	80,000	63,000	8	15	26.5	--	16
Hastelloy R-235	42,000	71,000	157,000	135,000	56	4	28	24	5
Udimet 500	125,000	114,000	195,000	176,000	31	29	31	26	14
Type 304 Stainless Steel	34,000	12,000	85,000	42,000	63	39	28.3	21.5	13
Hastelloy N*	45,500	31,600 (1300°F)	115,100	69,600 (1300)	50.7	30.0 (1300°F)	31.3	27.0 (1300°F)	33

*Wrought, Heat Treated at 2150° F, Rapid Air Cool

TABLE 19 CLASS 8 COBALT BASE ALLOYS

TENSILE PROPERTIES

TYPE OF MATERIAL	0.2% OFFSET YIELD STRENGTH (PSI)		ULTIMATE TENSILE STRENGTH (PSI)		ELONGATION % IN 2"		MODULUS OF ELASTICITY (10^6 PSI)		REF.
	80° F	1200° F	80° F	1200° F	80° F	1200° F	80° F	1200° F	
S-816	55,000	44,000	140,000	112,000	35	23	35	28	14
Haynes 25	67,000	35,000	156,000	92,000	64	54	32	26	5
Type 304 Stainless Steel	34,000	12,000	85,000	42,000	63	39	28.3	21.5	13

TABLE 20 CLASS 9, COPPER BASE ALLOYS

TENSILE PROPERTIES

TYPE OF MATERIAL	0.2% OFFSET YIELD STRENGTH (PSI)		ULTIMATE TENSILE STRENGTH (PSI)		ELONGATION % IN 2"		MODULUS OF ELASTICITY (10^6 PSI)		REF.
	80° F	1200° F	80° F	1200° F	80° F	1200° F	80° F	1200° F	
Copper ¼ Hard (tough pitch)	30,000	--	38,000	--	25	--	--	--	21
Beryllium-Copper	140,000	--	175,000	--	6	--	--	--	10
Cartridge Brass ¼ hard	40,000	--	54,000	--	43	--	--	--	21
Type 304 Stainless Steel	34,000	12,000	85,000	42,000	63	39	28.3	21.5	13

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TABLE 21 CLASS 10, REFRACTORY METALS AND ALLOYS

TENSILE PROPERTIES

TYPE OF MATERIAL	0.2% OFFSET YIELD STRENGTH (PSI)		ULTIMATE TENSILE STRENGTH (PSI)		ELONGATION % IN 2"		MODULUS OF ELASTICITY (10^6 PSI)		REF.
	80° F	1200° F (1600°F)	80° F	1200° F (1600°F)	80° F	1200° F (1600°F)	80° F	1200° F (1600°F)	
Molybdenum	85,000	45,000	91,000	51,000	10	22	45	39	4
Molybdenum + 1/2 Titanium	99,000	80,000 (1400°F)	132,000	94,000 (1400°F)	31	16 (1400° F)	46	40 (1400°F)	1
Zirconium	35,500	3,100	62,000	7,400	18	134	17	8.5	25
Zircaloy-2	41,000	6,400	71,000	41,000	21	80	16.7	6	12
AZ-3Z1	88,000	28,000 (600°C)	108,000	32,000 (600°C)	17	55 (600°C)	--	--	28
Tungsten	--	13,000	91,000	55,000	0	41	--	--	5
Tantalum	57,000	19,000	67,000	45,000	25	17	--	--	7
Columbium	37,000	14,000	44,000	42,000 (600°C)	19	22 (600°C)	15	--	2
Vanadium	--	--	81,000	36,000	22	38	18	--	3
Titanium 6Al-4V	130,000	65,000 (1000°F)	142,000	81,000 (1000°F)	13	35 (1000°F)	--	--	8
Beryllium	65,000	15,000	80,000	15,000	5	15	42	--	6
Type 304 Stainless Steel	34,000	12,000	85,000	42,000	63	39	28.3	21.5	13
Cb-1 Zr	21,400*	--	70,000	55,000	18.2**	--	--	--	

*Proportional limit, converted value

** 1 inch gage length

(Ref. - 2,34)

TABLE 22 CLASS 1, ALLOY STEEL

TYPE OF MATERIAL	CREEP PROPERTIES: TEST TEMPERATURE (°F)	STRESS (PSI)	MINIMUM CREEP RATE (%/HR)	STRESS - RUPTURE PROPERTIES: TEST TEMPERATURE (°F)	STRESS (PSI) FOR RUPTURE IN 1000 HRS	10,000 HRS	REF.
2¼ Cr + 1 Mo	1200	2300 4300	1×10^{-5} 1×10^{-4}	1200	8500	6200	13
Type 304 Stainless Steel	1200	4100 6900	1×10^{-5} 1×10^{-4}	1200	14,000	9700	13 & 14
481*	1200	20,200	1.4×10^{-2}	1200	20,200 (136 hrs)	--	32

*Normalized 2150° F and tempered 1300° F - 1 hr

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TABLE 23, CLASS 2, FERRITIC STAINLESS STEELS

TYPE OF MATERIAL	CREEP PROPERTIES: TEST TEMPERATURE (°F)	CREEP PROPERTIES: STRESS (PSI)	CREEP PROPERTIES: MINIMUM CREEP RATE (%/HR)	STRESS-RUPTURE PROPERTIES: TEST TEMPERATURE (°F)	STRESS (PSI) FOR RUPTURE IN 1000 HRS	STRESS (PSI) FOR RUPTURE IN 10,000 HRS	REF.
410	1200	1200	1×10^{-5}	1100	10,000	6900	13
		2000	1×10^{-4}				
430	1200	1500	1×10^{-5}	1200	5,000	3400	13
		2200	1×10^{-4}				
446	1200	800	1×10^{-5}	1200	4,000	2200	13
		1400	1×10^{-4}				
Type 304	1200	4100	1×10^{-5}	1200	14,000	9700	13 & 14
		6900	1×10^{-4}				

TABLE 24 CLASS 4, AUSTENITIC STAINLESS STEELS

TYPE OF MATERIAL	CREEP PROPERTIES: TEST TEMPERATURE (°F)	STRESS (PSI)	MINIMUM CREEP RATE (%/HR)	STRESS-RUPTURE PROPERTIES: TEST TEMPERATURE (°F)	STRESS (PSI) FOR RUPTURE IN 1000 HRS	STRESS (PSI) FOR RUPTURE IN 10,000 HRS	REF.
304	1200	4100	1×10^{-5}	1200	14,000	9,700	13 & 14
		6900	1×10^{-4}				
316	1200	6600	1×10^{-5}	1200	24,700	18,200	13
		12700	1×10^{-4}				
347	1200	6100	1×10^{-5}	1200	17,500	11,000	13
		8200	1×10^{-4}				
321	1200	8000	1×10^{-4}	1200	17,500	9,800	13

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TABLE 25 CLASS 6, AUSTENITIC SUPER ALLOYS

TYPE OF MATERIALS	CREEP PROPERTIES: TEST TEMPERATURE (°F)	STRESS (PSI)	MINIMUM CREEP RATE (%/HR)	STRESS-RUPTURE PROPERTIES: TEST TEMPERATURE (°F)	STRESS (PSI) FOR RUPTURE IN 1000 HRS	10,000 HRS	REF.
A - 286	1200	29,500	1×10^{-4}	1200	46,000	32,000	14
19 - 9 DL	1200	20,000	1×10^{-4}	1200	37,000	31,000	14
N - 155	1200	29,000	1×10^{-4}	1200	42,000	35,000	14
Type 304 Stainless Steel	1200	4,100 6,900	1×10^{-5} 1×10^{-4}	1200	14,000	9,700	13 & 14

TABLE 26 CLASS 7, NICKEL BASE ALLOYS

TYPE OF MATERIAL	CREEP PROPERTIES: TEST TEMPERATURE °F	CREEP PROPERTIES: STRESS (PSI)	CREEP PROPERTIES: MINIMUM CREEP RATE (%/HR)	STRESS-RUPTURE PROPERTIES: TEST TEMPERATURE °F	STRESS (PSI) FOR RUPTURE IN 1000 HRS	STRESS (PSI) FOR RUPTURE IN 10,000 HRS	REF.
Nickel	--	--	--	--	--	--	
Inconel X	1200	64,000	1×10^{-4}	1200	55,000	--	1
Hastelloy B	--	--	--	1200	40,500	--	22
Hastelloy R-235	--	--	--	1200	75,000 (100 hrs)	--	5
Udimet 500	--	--	--	1350	69,000	46,000	14
Type 304 Stainless Steel	1200	4,100 6,900	1×10^{-5} 1×10^{-4}	1200	14,000	9,700	13 & 14
Hastelloy N	--	--	--	1300	20,000 (338.6 hrs)	--	33

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TABLE 27 CLASS 8, COBALT BASE ALLOYS

TYPE OF MATERIAL	CREEP PROPERTIES: TEST TEMPERATURE (°F)	CREEP PROPERTIES: STRESS (PSI)	CREEP PROPERTIES: MINIMUM CREEP RATE (%/HR)	STRESS-RUPTURE PROPERTIES: TEST TEMPERATURE (°F)	STRESS-RUPTURE PROPERTIES: STRESS (PSI) FOR RUPTURE IN 1000 HRS	STRESS-RUPTURE PROPERTIES: STRESS (PSI) FOR RUPTURE IN 10,000 HRS	REF.
S 816	1200	42,000	1×10^{-4}	--	--	--	1
Haynes 25	--	--	--	1200	55,000 (100 hrs)	--	5
Type 304 Stainless Steel	1200	4,100 6,900	1×10^{-5} 1×10^{-4}	1200	14,000	9,700	13 & 14

TABLE 28 CLASS 10, REFRACTORY METALS AND ALLOYS

TYPE OF MATERIAL	CREEP PROPERTIES: TEST TEMPERATURE (°F)	STRESS (PSI)	MINIMUM CREEP RATE (%/HR)	STRESS-RUPTURE PROPERTIES: TEST TEMPERATURE (°F)	STRESS (PSI) FOR RUPTURE IN 1000 HRS	STRESS (PSI) FOR RUPTURE IN 10,000 HRS	REF.
Molybdenum	1832	10,000	5.5×10^{-5}	--	--	--	4
Molybdenum + 1/2 Titanium	--	--	--	--	--	--	
Zirconium	--	--	--	--	--	--	
Zircaloy-2	1050	2,800	1×10^{-2}	--	--	--	17
AI 321	1200	2,000 1,500	1×10^{-2} 1.1×10^{-3}	--	--	--	25
Tungsten							
Tantalum							
Columbium	1112	8,000 16,000	6×10^{-4} 1×10^{-3}	--	--	--	2
Vanadium	1112	8,000	1.7×10^{-5}	--	--	--	3
Titanium							
Beryllium	1250	2,000 3,190	9×10^{-4} 2.8×10^{-1}	1200	2150	2000 (2500 hrs)	6
Type 304 Stainless Steel	1200	4,100 6,900	1×10^{-5} 1×10^{-4}	1200	14000	9700	13 & 14

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