MASTER

WFPS-TME-031

**Westinghouse Electric Corporation
Fusion Power Systems Department**

COMPILATION OF TFTR MATERIALS DATA

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COMPILATION OF TFTR MATERIALS DATA

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ABSTRACT

In order to document the key thermophysical property data used in the conceptual design of Tokamak Fusion Test Reactor (TFTR) systems and components, a series of data packages has been prepared. It is expected that data for additional materials will be added and the information already provided will be updated to provide a project-wide data base.

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1.0 INTRODUCTION

This report contains a compilation of some of the materials properties that have been used in the Tokamak Fusion Test Reactor (TFTR) Conceptual Design efforts. This compilation is certainly not definitive, documentation is provided for materials data used to date. A basis has been provided for a future project-wide materials data base which will be considerably widened in scope over the information presented herein.

A number of the curves included in the sections of this report are from materials data books prepared by Westinghouse for other projects, but the data are referenced to the original sources, which are more generally accessible. Other data is from sources researched in preparing this report. The data on any particular material is by no means complete but contains basic information which, it is expected, will be added to as the project progresses and the information is required and/or developed.

The minimum expected values for ultimate and yield strengths are identical to those used by the ASME Boiler and Pressure Vessel Code to establish allowable stresses. It is assumed in the Code that 95% of the data points will be above the minimum curve. Data indicated as average is that in which there was sufficient data available within a $\pm 10\%$ band to permit the use of an averaging process to prepare a single curve for ease in using the data. Some curves are 80% of the average values and are so stated.

Tritium properties have been compiled and reported in TME-004, "Tritium Properties and Related Quantities Used in the TFTR Conceptual Design," by H. J. Garber.

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1.0 BASIC DATA

1.1 GENERAL

Types 304 and 304 L are the most commonly used of the austenitic stainless steels. 304L is the low carbon grade. These materials have high corrosion resistance, very good formability, and are readily weldable by all techniques.

The properties given in section E are for AISI 304 and are average, except for tensile ultimate strength, tensile yield strength, elongation, and reduction in area. These latter properties are 80% of average.

1.2 COMMERCIAL DESIGNATIONS

Wrought: AISI 304, AISI 304 L

Cast: CF - 8, CF - 3

Available Forms, Specifications, Suppliers

Forms and Conditions	Specifications
Sheet, Strip, and Plate (Solution-Treated)	MIL-S-5059 QQ-S-766, AMS 5513
Tubing, Hydraulic (Cold Drawn)	MIL-T-6845, AMS 5566
Tubing, Seamless and Welded (Sol.- Treated)	MIL-T-8506 AMS 5560, AMS 5565
Bar Forgings, Tubing (Solution-Treated)	MIL-S-7720, QQ-S-763 AMS 5639
Wire (Sol. Treated)	AMS 5697
Sheet, Strip, and Plate (304 L Sol. Treated)	MIL-S-4043

1.3 CHEMICAL COMPOSITION (WT. %)

ELEMENT	C*	Mn	Si	P	S	Cr	Ni	Mo
MAXIMUM	0.08	2.00	1.00	.040	.030	20.0	11.0	0.50
MINIMUM	—	—	—	—	—	18.00	8.00	—
	*For 304 L, Max. C Content is 0.030%						Cu 0.50	Fe Bal.

1.4 ROOM TEMPERATURE PROPERTIES (Average Unless Otherwise Noted)

1.4.1 Mechanical Properties

	Sheet Strip	Annealed Thickness, Inches	Plate, Bar	
Tensile Ultimate Strength	F_{TU}			PSI
	68,000		68,000	
Tensile Yield Strength	F_{TY}			PSI
	28,000		24,000	
Comp. Yield Strength	F_{CY}			PSI
Ultimate Shear Strength	F_{SU}			PSI
Shear Yield Strength	F_{SY}			PSI
Ultimate Bearing Strength	F_{BRU}			PSI
$e/D = 1.5$				
$e/D = 2.0$				
Yield Bearing Strength	F_{BRY}			PSI
$e/D = 1.5$				
$e/D = 2.0$				
Elongation	e			%
	40		53	

Reduction of Area	RA	%
	50	
Modulus of Elasticity	E	10^6 PSI
	26	
Comp. Modulus of Elasticity	E_C	10^6 PSI
Modulus of Rigidity	G	10^6 PSI
(Dynamic)	13	
Poisson's Ratio		
	0.25	
Hardness	R_B	
	80	
Plastic Bending Modulus		

1.4.2 Physical Properties

Density	ρ	LB/IN ³
	0.287	
Specific Heat	C	BTU/LB - °F
	0.12	
Thermal Conductivity	k	$\frac{\text{BTU} - \text{FT}}{\text{HR} - \text{FT}^2 - ^\circ\text{F}}$
	8.9	
Mean Coeff. Lin. Thermal Expans.	α	$\frac{10^{-6} \text{ IN.}}{\text{IN.} - ^\circ\text{F}}$
(70-100°F)	8.7	
Electrical Resistivity	R	MICROHM - IN
	28	

1.4.3 Magnetic Properties

Non-magnetic in the annealed condition, but becomes slightly magnetic when cold worked.

1.5 THERMOPHYSICAL EFFECTS

Melting Range	
	2550 - 2650°F

Phase Changes

Subject to carbide precipitation at 800° - 1600°F.

Thermal Conductivity Vs. Temperature

Temperature (°F)	$k \left(\frac{\text{BTU} \cdot \text{FT}}{\text{HR} \cdot \text{FT}^2 \cdot ^\circ\text{F}} \right)$
- 423	1.33
- 320	4.00
- 200	6.11
0	8.05
75	8.44
200	8.95
400	9.94
600	10.95
800	11.95
1000	13.21
1200	14.11
1350	15.06

1.6 CHEMICAL PROPERTIES

General corrosion resistance to various atmospheres, most acids, steam and combustion gases, is very good.

Passivating is necessary to develop best corrosion resistance.

Oxidation resistance is good up to 1700°F for continuous service and to 1600°F for intermittent service.

Intergranular corrosion after welding or heating may occur in type 304.

1.7 NUCLEAR PROPERTIES

Austenitic stainless steels retain their high impact strength after irradiation.

1.8 NOMENCLATURE

R In fatigue the algebraic ratio of the minimum stress to the maximum stress in one cycle, that is, $R = \frac{S_{MIN}}{S_{MAX}}$

ELC Extra low carbon

L Low carbon grade

1.9 SERVICE LIMITS

Type 304 L

- 423°F to 800°F (Not recommended above 800°F because of relatively low strength.)

1.10 PROCESSING

1.10.1 Surface Treatment

Scale may be removed by a solution of 15 - 20 percent nitric acid and 1 - 3 percent hydrofluoric acid at 120°F to 140°F, for 20 to 30 minutes. Scale is more readily removed when parts have been heated in air.

Chlorinated cleaners, such as trichloroethylene, should be avoided, as these may contribute to stress-corrosion cracking of the alloy.

1.10.2 Thermal Treatment

Furnace atmospheres should be neutral or slightly oxidizing. Heating with high sulfur fuels should be avoided.

Bright annealing is done in a dry hydrogen, cracked ammonia, or argon atmosphere with a dew point of - 80°F maximum.

1.10.3 Sheet and Tubing

1900 to 1950°F, 10 minutes hold at temperature, air cool up to 0.064 inch in thickness, water quench 0.065 inch and thicker.

1.10.4 Joining

Can be welded readily by all methods. Type 308 weld wire generally used.

Welding:

For parent metal welded to itself, select one of the following weld rods:

AISI 308/MIL-R-5031, CL. 1

AISI 308 ELC/MIL-R-5031, CL. 16

ER 308/ASTM-A-371, CL. ER308

ER 308L/ASTM-A-371, CL. ER308L

1.10.5 Forming

Formability:

Excellent formability in the annealed condition may require intermediate annealing in severe forming operations.

Forging:

Starting forging temperature 2300°F maximum, finishing temperature 1500°F minimum. Severe reduction below 1700°F should be avoided.

Castability:

Excellent.

1.10.6 Machinability

Machinability is about 35% of Bessemer Steel screw stock.

2.0 MECHANICAL PROPERTIES (As Function of Temperature)

2.1 SHORT TERM

2.1.1 Static

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APPLICABLE PRODUCT FORMS: See notes below.

NOTES: Product forms: 517 MPa (75,000 PSI): SA-182, 213, 240, 249, 312, 376, 452, 479
483 MPa (70,000 PSI): SA-336 and 430.

Figure 2.1-1

APPLICABLE PRODUCT FORMS: All product forms.

NOTES: Irradiated material originally annealed. The ultimate tensile strength values are keyed to normalized minimum values for unirradiated material (75,000 PSI at R.T.).

Figure 2.1-2

APPLICABLE PRODUCT FORMS: All product forms.

NOTES: This curve is normalized to a room temperature minimum of 207 MPa (30,000 PSI). Use of this curve above 533°C (1000°F) is limited to material with a carbon content $\geq 0.04\%$.

Figure 2.1-3

APPLICABLE PRODUCT FORMS: All product forms.

NOTES: Irradiated material, originally annealed. 0.2% offset yield strength, keyed to normalized minimum values for unirradiated material.

Figure 2.1-4

APPLICABLE PRODUCT FORMS: As noted on curves.

NOTES: The specified room temperature minimums are noted on the curves.

The curves are based on tensile tests of uniaxial, solid specimens, performed according to ASTM specifications.

Figure 2.1-5

APPLICABLE PRODUCT FORMS: As noted on graph.

NOTES: The curves are based on a percentage of the normalized minimum total elongation values. The data is from tensile tests of uniaxial, solid specimens, performed according to ASTM specifications.

Figure 2.1-6

APPLICABLE PRODUCT FORMS: As noted on graph.

NOTES: Irradiated material, originally annealed. Total elongation for the temperature range 371°C (700°F) to 649°C (1200°F).

Figure 2.1-7

APPLICABLE PRODUCT FORMS: As noted on graph.

NOTES: Irradiated material, originally annealed. Total elongation for the temperature range 371°C (700°F) to 649°C (1200°F).

Figure 2.1-8

APPLICABLE PRODUCT FORMS: All product forms.

NOTES: The shape of the curve between room temperature and 538°C (1000°F) was approximated using the general shape of an ultimate strength curve.

Figure 2.1-9

APPLICABLE PRODUCT FORMS: All product forms.

NOTES:

Figure 2.1-10

APPLICABLE PRODUCT FORMS: All product forms.

NOTES:

Figure 2.1-11

APPLICABLE PRODUCT FORMS: All product forms.

NOTES: These curves were calculated from the equation: $E/(2(1 + \nu))$

Figure 2.1-11

APPLICABLE PRODUCT FORMS: All product forms.

NOTES: The original data were an average for one heat of material. The material was tested at a strain rate of $\sim 0.0022 \text{ min}^{-1}$.

Figure 2.1-13

APPLICABLE PRODUCT FORMS: All product forms.

NOTES:

Figure 2.1-14

2.2 LONG TERM

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Figure 2.2-2 Stress to Rupture and Creep

Figure 2.2-3 Stress Vs. Strain

Figure 2.2-4 Stress Vs. Strain

AISI 304 SS

FATIGUE STRENGTH

Figure 2.2-1

AISI 304
STAINLESS STEEL

STRESS TO RUPTURE
AND CREEP
TIME

Figure 2.2-2

**AISI 304
STAINLESS STEEL**

**STRESS VS STRAIN
AS FUNCTION OF
TEMPERATURE**

Figure 2.2-3

**AISI 304
STAINLESS STEEL**

**STRESS VS STRAIN
AS FUNCTION OF
TEMPERATURE**

2-26
STRESS
1000 PSI

Figure 2.2-4

3.0 PHYSICAL PROPERTIES

3.1 THERMAL PROPERTIES

Figure 3.1-1 Thermal Expansion/Specific Heat

AISI 304
STAINLESS STEEL

THERMAL EXPANSION
SPECIFIC HEAT

THERMAL CONDUCTIVITY

Figure 3.1-1

4.0 CHEMICAL PROPERTIES

5.0 NUCLEAR PROPERTIES

6.0 REFERENCES

- 6.1 Aerospace Structural Metals Handbook.
- 6.2 Simmons, W. F. and Cross, H. C., "The Elevated Temperature Properties of Stainless Steels," ASTM STP-124, 1952.
- 6.3 Simmons, W. F. and Van Echo, T. A., "The Elevated Temperature Properties of Stainless Steels," ASTM DS5-S1, 1965.
- 6.4 Cryogenic Materials Data Book, ML-TDR-64-280 (PB171809, Revised) AFSC, Wright-Patterson AFB, Aug 1964, with Supplements through July 1965.
- 6.5 Low Temperature Data Sheet, Types 304 and 304 L Stainless Steels, INCO, March 1963.

SECTION 3.0
TYPE 305 STAINLESS STEEL

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(Elec. Resistivity, Mag. Resistivity, etc.)

3.3

MISCELLANEOUS (Viscosity, Density)

4.0 CHEMICAL PROPERTIES

5.0 NUCLEAR PROPERTIES

6.0 REFERENCES

1.0 BASIC DATA

1.1 GENERAL

Type 305 austenitic stainless steel is the member of the 18 Cr-8Ni steel family having the highest nickel content considered to be within this classification. It is, therefore, the austenitic stainless steel with the lowest rate of strain hardening. It is used in sheet, strip and plate form for difficult drawing, spinning and other forming operations and in wire form for severe upsetting. It also becomes less magnetic on cold work than other 18-8 steels, particularly Type 301. This steel has a higher carbon content than Type 304 and, therefore, a greater susceptibility to intergranular corrosion after exposure at 800 to 1500 F. The properties of this alloy are otherwise nearly identical to those of Type 304.

1.2 COMMERCIAL DESIGNATIONS

AISI Type 305 austenitic stainless steel, 18-8 FS stainless steel, 18-12 steel, 30305.

Available Forms, Specifications

Form	AMS	ASTM
Sheet, strip and plate	5514A	A-167, A-240
Bar and billet		A-276, A-314
Tube		A-249
Forging		A-473
Wire; rope and safety	5685D	A-492
Wire, riveting and cold heading	5686A	A-493
Wire, cold Finished or cold drawn rounds and shapes		A-580
Wire, weaving		A-478

This steel is available in plate, sheet, strip, bar, shapes billet, forging and wires. Plate, sheet, strip, bar, shapes and wires may be obtained in hot finished and annealed, cold finished and annealed and cold worked conditions.

1.3 CHEMICAL COMPOSITION (%)

Source	Ref. 6.9		Ref. 6.10		Ref. 6.11	
Alloy	Fe-18Cr-12Ni (Type 305)					
Form	Plate, sheet, Strip		Wire, safety		Wire, riveting	
	Percent		Percent		Percent	
	min.	max.	min.	max.	min.	max.
Carbon	-	0.12	-	0.08	-	0.08
Manganese	-	2.00	-	2.00	-	2.00
Phosphorous	-	0.040	-	0.040	-	0.040
Sulfur	-	0.030	-	0.030	-	0.030
Silicon	-	1.00	-	1.00	-	1.00
Chromium	17.00	19.00	17.00	19.00	17.00	19.00
Nickel	10.00	13.00	10.00	13.00	10.00	13.00
Copper	-	0.50	-	0.50	-	0.50
Molybdenum	-	0.50	-	0.50	-	0.50
Iron	Balance		Balance		Balance	

Source	Ref. 6.12 to 6.21			
Alloy	Fe-18Cr-12Ni (Type 305)			
Form	Sheet, strip and plate; bar and billet; tube; forging; and wire		Bar and wire for cold heading and cold forging	
	Percent		Percent	
	minimum	maximum	minimum	maximum
Carbon	-	0.12	-	0.12
Manganese	-	2.00	-	2.00
Phosphorous	-	0.045	-	0.045
Sulfur	-	0.030	-	0.030
Silicon	-	1.00	-	1.00
Chromium	17.00	19.00	17.00	19.00
Nickel	10.00	13.00	11.00	13.00
Iron	Balance		Balance	

1.4 ROOM TEMPERATURE PROPERTIES

1.4.1 Mechanical Properties

<u>Tensile ultimate strength</u>	<u>FTU</u>	<u>psi</u>
annealed		85,000

<u>Tensile yield strength</u>	<u>FTY</u>	<u>psi</u>
annealed		36,500

<u>Compressive yield strength</u>	<u>FCY</u>	<u>psi</u>
-----------------------------------	------------	------------

<u>Shear strength</u>	<u>FSU</u>	<u>psi</u>
-----------------------	------------	------------

<u>Ultimate bearing strength</u>	<u>FBRU</u>	<u>psi</u>
----------------------------------	-------------	------------

<u>Elongation</u>	<u>e</u>	<u>%</u>
annealed		52.5

<u>Reduction of Area</u>	<u>RA</u>	<u>%</u>
--------------------------	-----------	----------

<u>Modules of Elasticity</u>	<u>E</u>	<u>10⁶ psi</u>
28 ⁽²⁾		

<u>Modules of Rigidity</u>	<u>G</u>	<u>10⁶ psi</u>
----------------------------	----------	---------------------------

<u>Compressive Modules of Elasticity</u>	<u>Ec</u>	<u>10⁶ psi</u>
--	-----------	---------------------------

<u>Hardness</u>	<u>RB</u>	
annealed		80

1.4.2 Physical Properties

Density	ρ	lb/in ³
		0.29
Specific Heat	c	BTU/lb °F
		0.12
Thermal Conductivity		BTU/hr/°F/st
		9.4 (212°F)
Coefficient of Thermal Expansion	γ	°F ⁻¹
		(2)
		9.6×10^{-6} (32 - 212°F)
		9.3×10^{-6} (32 - 572°F)
Electrical Resistivity	Ω	Microhm-cm
		72 (2)

1.4.3 Magnetic Properties

This steel is non-magnetic in the annealed condition. It becomes slightly magnetic when severely cold worked as a result of transformation of austenite to ferrite (martensite)(this effect is less pronounced than for the other 18-8 grades).

1.4.4 Chemical Properties

Excellent atmosphere resistance. General corrosion resistance of this steel is similar to that of Type 304.

This steel is only slightly embrittled by high pressure (10,000 psi) gaseous hydrogen environment.

1.4.5 Nuclear Properties

The effect of neutron irradiation on room temperature tensile properties of annealed bar is given in the following table:

Source	Ref. 6.4	
Alloy	Fe-18 CR-12 Ni (Type 305)	
Form	Bar	
Condition	Annealed	
	Unirradiated	Irradiated*
F _{tu} - ksi	98.0	103.6
F _{ty} - ksi	32.1	71.4
* Irradiation - 3.9×10^{19} n/cm ² at 80 C		

1.5 SPECIAL CONSIDERATIONS

When chromium-nickel steels containing more than about 0.04C are subjected to annealing at temperatures of 1850 to 2050 F and are then reheated to or held at temperatures of approximately 800 to 1600F, chromium carbides will precipitate at the austenite boundaries (Ref. 6.5, pg. 24). This intergranular precipitation or sensitization promotes intergranular corrosion cracking and reduces corrosion resistance of these steels. Heat treatment and welding conditions should be chosen to avoid carbide formation. Additions of columbium and titanium are used to stabilize these alloys and reduce intergranular corrosion sensitivity.

1.6 PROCESSING

Surface Treatment

See ASTM A 380-57 entitled "Recommended Practice/or Descaling and Cleaning Stainless Steel Surfaces."

Thermal Treatment

Anneal or solution heat treat. 1850 to 2000 F, 1/2 to 1 hour per inch thickness, 2 hour minimum for plate, air cool or quench, depending on section size. Cooling to 800 F maximum should be within 3 minutes.

This steel can be hardened only by cold working, and this to a lesser degree than the other steels of the 18-8 family.

1.7 JOINING

Thermal properties of this steel should be considered in the design of welded equipment and welding fixtures to minimize warpage or distortion at the weld. Welding rods of similar chemical analysis, or with slightly higher chromium-nickel content, as the base metal should be used. The use of fluxes, coated rods and inert gas shields is recommended.

1.8 FORMING

General. Forming of this steel differs in various respects from that of Types 301 and 302, but it is similar to that of Type 304. Because of its lower strain hardening, Type 305 requires less power and requires fewer intermediate anneals in multi-stage forming. Its stretch forming ability, however, is lower than that of Types 301 and 302, because of its lower elongation.

Deep drawing of this steel is usually performed with the same or less reduction in the first draw than that of Types 301 and 302, but without intermediate anneals before the second, and possibly further draws. The reductions in these draws should be considerably lower than those possible for Type 301 which needs annealing after each draw. Type 305 also has a greater tendency to become thin at sharp radii than Types 301 and 302. Annealing is necessary if the hardness exceeds 35 to 40 R_c .

Type 305 is preferred for spinning applications because of its lower strain hardening. The surface should be kept clean and free from foreign particles during spinning.

1.9 MACHINABILITY

Machining and Grinding. All 300 series austenitic stainless steels can be machined. Use of high speed or carbide tools, positive feed, and abundant flow of coolant or lubricant is recommended.

2.0 MECHANICAL PROPERTIES

2.1 SHORT TERM

2.1.1 Static

Figure 2.1-1 Effect of Cold Rolling on Tensile Properties

Figure 2.1-2 Effect of Cold Drawing on Tensile Properties of Coiled Bar

Figure 2.1-3 Effect of Cold Rolling on Hardness of Various 18-8 Stainless Steel Sheets

Table 2.1-1 Mechanical Properties in Various Environments

Table 2.1-2 Range of Tensile Properties and Hardness for Various Tempers and Diameters of Cold Draw Wire

EFFECT OF COLD ROLLING
ON TENSILE PROPERTIES OF STRIP.

EFFECT OF COLD DRAWING
ON TENSILE PROPERTIES OF BAR.

Figure 2.1-1

EFFECT OF COLD DRAWING
ON TENSILE PROPERTIES OF COILED BAR.

Figure 2.1-2

EFFECT OF COLD ROLLING ON
HARDNESS OF VARIOUS 18-8 STAINLESS
STEEL SHEETS.

Figure 2.1-3

TABLE 2.1-1
MECHANICAL PROPERTIES IN VARIOUS ENVIRONMENTS

Source	Ref. 6.6	
Alloy	Fe-18Cr-12Ni (Type 305)	
Condition	Anneal + Cold Drawn	
Environment	10,000 psi He [*]	10,000 psi H ₂
F _{tu} - ksi	90*	87
F _{ty} - ksi	51	-
e(1.25 in) - percent	63	65
RA - percent	78	75
Notch Strength - ksi (K _t 8.6)	165*	147
RA (Notched Bar) - percent	19	17
*He was contaminated with H ₂ . Strength reported are those for tests in ambient air minus 10 ksi to compensate for effect of 10,000 psi pressure.		

TABLE 2.1-2

RANGE OF TENSILE PROPERTIES AND
HARDNESS FOR VARIOUS TEMPER AND DIAMETERS OF COLD DRAW WIRE

Source	Ref. 6.7, p. 6											
Alloy	Fe-18Cr-12Ni (Type 305)											
Form	Wire											
Condition	Cold Drawn											
Temper	1/4 Hard			1/2 Hard			3/4 Hard			Full Hard		
Dia. - in (a)	A	B	C	A	B	C	A	B	C	A	B	C
F_{tu} - ksi	130 to 165	130 to 160	110 to 130	165 to 200	150 to 190	140 to 160	200 to 250	180 to 230	160 to 190	230 to 300	210 to 260	190 to 220
F_{ty} - ksi	100 to 140	95 to 125	90 to 110	150 to 180	120 to 165	110 to 130	180 to 210	150 to 200	130 to 160	210 to 260	180 to 240	160 to 190
e(2 in)-percent	20 to 30	15 to 25	20 to 30	12 to 19	11 to 18	12 to 20	7 to 12	6 to 12	8 to 12	1 to 2	2 to 5	3 to 6
Hardness R_C	-	-	23 to 28	-	-	29 to 32	-	-	33 to 37	-	-	38 to 43
(a)	A - 0.002 to 0.020 inch B - 0.021 to 0.125 inch C - 0.125 to 0.375 inch											

2.1.2 Dynamic

2.2 LONG TERM

2.3 CYCLIC LOAD PROPERTIES

Figure 2.3-1 Fatigue Crack Growth in Annealed Sheet

Figure 2.3-2 Fatigue Crack Growth in Cold Rolled Sheet

FATIGUE CRACK GROWTH
IN ANNEALED SHEET
(LONGITUDINAL OR RW ORIENTATION)

FATIGUE CRACK GROWTH
IN ANNEALED SHEET
(TRANSVERSE OF WR ORIENTATION)

Figure 2.3-1

FATIGUE CRACK GROWTH IN
COLD ROLLED SHEET
(LONGITUDINAL OR RW ORIENTATION)

FATIGUE CRACK GROWTH IN
COLD ROLLED SHEET
(TRANSVERSE OR WR ORIENTATION)

Figure 2.3-2

3.0 PHYSICAL PROPERTIES

3.1 THERMAL PROPERTIES

Table 3.1-1 Thermal Expansion

TABLE 3.1-1
THERMAL EXPANSION

Source	Ref. 6.5
Alloy	Fe-18Cr-12Ni (Type 305)
Temperature Range F	Mean Coefficient of Thermal Expansion 10^{-6} in/in/F
32-212	9.6
32-600	9.9
32-1000	10.2
32-1200	10.4

3.2 ELECTRICAL/MAGNETIC PROPERTIES

Table 3.2-1 Effects of Cold Reduction on Permeability at Various Temperatures at $H = 200$ Oersteds

Figure 3.2-1 Effect of Cold Reduction on Permeability of Cold Rolled Strip

TABLE 3.2-1

EFFECT OF COLD REDUCTION ON PERMEABILITY AT
VARIOUS TEMPERATURES AT H=200 OERSTEDS

Source	Ref. 6.8	
Alloy	Fe-18Cr-12Ni (Type 305)*	
Condition	Anneal + Cold Reduced	
Percent Cold Reduction	Temperature Range - F	Permeability at H= 200 Oersteds
0	20-100	1.003
25	20-300	1.005
50	20-871	1.025
*C 1.069, Mn 0.94, P 0.021, S 0.013, Si 0.52, Cr 17.19, Ni 11.65

Figure 3.2-1 EFFECT OF COLD REDUCTION ON
PERMEABILITY OF COLD ROLLED STRIP.

4.0 CHEMICAL PROPERTIES

5.0 NUCLEAR PROPERTIES

**Effect of neutron irradiation on room temperature tensile properties of annealed bar ,
see Section 1.4.5.**

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- 6.21 ASTM A580-67, Standard Specification for Stainless and Heat-Resisting Steel Wire (December 12, 1967).

SECTION 4.0

316 STAINLESS STEEL

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4.0 CHEMICAL PROPERTIES

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6.0 REFERENCES

1.0 BASIC DATA

1.1 GENERAL

AISI 316 is an austenitic stainless steel of the 18-8 class, the chemistry having been modified by the addition of molybdenum. As a result, this alloy has a corrosion resistance superior to that of other austenitic steel grades for certain applications.

The property values given in Section 1.4 are averages, except for ultimate tensile strength, tensile yield strength, elongation, and reduction of area, which are 80% of average.

1.2 COMMERCIAL DESIGNATIONS

Wrought: 18 - 8 Mo Stainless Steel

Cast: CF3M, CF8M, CF12M (A. C. I. Designations)

Available Forms, Specifications, Suppliers

Forms and Conditions	Specifications
Sheet, Strip and Plate	MIL-S-5059 QQ-S-766 AMS 5524
Bar, Forgings, Forging Stock	MIL-S-7720 QQ-S-763 AMS 5648
Spring Wire	QQ-W-423
Tubing, Seamless	AMS 5573

Suppliers

Allegheny Ludlum Steel Co.
Crucible Steel Co.
Republic Steel Co.
U. S. Steel Co.

1.3 CHEMICAL COMPOSITION (%)

ELEMENT	C	Mn	Si	P	S	Cr	Ni	Mo
MAXIMUM	0.08	2.00	1.00	.045	.030	18.0	14.0	3.00
MINIMUM	—	—	—	—	—	16.0	10.0	2.00

1.4 ROOM TEMPERATURE PROPERTIES (Average Unless Otherwise Noted)

1.4.1 Mechanical Properties

<u>Sheet, Strip</u> <u>Annealed</u>	<u>Plate</u> <u>Annealed</u>	<u>Bar</u> * * *	
Tensile Ultimate Strength		F_{TU}	PSI
72,000	68,000	67,500	72,000
Tensile Yield Strength		F_{TY}	PSI
32,000	28,000	30,000	48,000
Comp. Yield Strength		F_{CY}	PSI
Shear Strength		F_{SU}	PSI
Ultimate Bearing Strength		F_{BRU}	PSI
Elongation		e	%
40	44	40	36
Reduction of Area		RA	%
		66	
Modulus of Elasticity		E	10^6 PSI
		26.3	

Modulus of Rigidity	G	10^6 PSI
	11.0	

Comp. Modulus of Elasticity	E_C	10^6 PSI
-----------------------------	-------	------------

Hardness	Rockwell		
R_B 85	R_B 82	R_B 78	R_B 91

Plastic Bending Modulus

*Cold Worked 13% Before Annealing

**Cold Drawn, 1-in. Dia.

1.4.2 Physical Properties

Density	ρ	LB/IN ³
	0.288	

Specific Heat	C	BTU/LB - °F
	10.5	

Thermal Conductivity	k	$\frac{\text{BTU} - \text{FT}}{\text{HR} - \text{FT}^2 - ^\circ\text{F}}$
	7.87	

Mean Coeff. Lin. Thermal Expans. (75-100°F)	α	$\frac{10^6 \text{ IN.}}{\text{IN.} - ^\circ\text{F}}$
	8.3	

Electrical Resistivity	R	MICROHM - IN.
	32.0	

1.4.3 Magnetic Properties

Non-magnetic in annealed condition. Formation of ferrite in severely cold worked material will result in very small increase in permeability.

1.4.4 Chemical Properties

Superior corrosion resistance, when compared to other austenitic stainless steels, on exposure to sea water and conditions where particles are deposited on surface.

Oxidation resistance good for continuous service up to 1600°F and for intermittent service up to 1500°F. Scales severely at approximately 1650°F. This temperature varies with type of atmosphere and other conditions.

1.4.5 Nuclear Properties

Austenitic stainless steels retain their high impact strength after irradiation.

1.5 SPECIAL CONSIDERATIONS

Service Limits

-423°F to 1600°F (Continuous)

-423°F to 1500°F (Intermittent)

1.6 PROCESSING

Surface Treatment

Scale may be removed by a solution of 15 to 20 percent nitric acid and 1 to 3 percent hydrofluoric acid at 120 to 140 F, for 20 to 30 minutes. Scale removal is more easily accomplished when parts have been heated in air.

Chlorinated hydrocarbon cleaners, such as trichloroethylene, should be avoided since they may contribute to stress-corrosion cracking.

Thermal Treatment

Avoid prolonged heating at temperatures from 800° to 1600°F. All heating should be conducted in air or inert atmospheres such as helium, argon, or dissociated ammonia.

Annealing

Wrought Products:

1850 - 2150°F, air cool or quench depending on section size. 1950°F minimum for sheet.

Casting:

1950 - 2100°F, air cool or quench. Use low side of temperature range for CF-8M; High side (above 2000°F) for CF-12M.

Stabilizing for High-Temperature Service

1625 - 1675°F, 2 - 4 hr. furnace or air cool

Stress Relief

400 - 750°F, 1/2 to 2 hr

Alloy can only be hardened by cold work.

1.7 JOINING

May be welded by conventional techniques. Oxyacetylene welding is not advisable for castings because of possible impairment of corrosion resistance due to carbon pick-up and possibility of sensitization.

Welding

For parent metal welded to itself, select one of the following weld rods:

AISI 316/MIL-R 5031, CL. 4

AISI 316 ELC/MIL-R-5031, CL. 17

ER 316/ASTM-A-371, CL. ER316

ER 316L/ASTM-A-371, CL. ER316L

1.8 FORMING

Forming should be done at room or forging temperatures, but not in the carbide precipitation range.

1.9 MACHINABILITY

About 50% of that of mild carbon steels.

2.0 MECHANICAL PROPERTIES (As Function of Temperature)

2.1 SHORT TERM

2.1.1 Static

Figure 2.1-1	Ultimate Tensile Strength (Minimum Expected)
Figure 2.1-2	Yield Strength (Minimum Expected)
Figure 2.1-3	Total Elongation (Minimum Expected)
Figure 2.1-4	Impact Strength Rockwell Hardness
Figure 2.1-5	Uniform Elongation (Minimum Expected)
Figure 2.1-6	Poisson's Ratio
Figure 2.1-7	Young's Modulus
Figure 2.1-8	Shear Modulus

APPLICABLE PRODUCT FORMS: See notes below.

NOTES: For 75,000 psi...SA - 182, 213, 240, 249, 312, 376, 452, 479. For 70,000 psi...SA - 336, 430.
Do not use for fuel cladding.

Figure 2.1-1 Ultimate Tensile Strength (Minimum Expected)

APPLICABLE PRODUCT FORMS: All product forms (except fuel clad).

NOTES: Use of these values above 538 Deg C (1000 Deg F) is limited to material with carbon content greater than or equal to 0.04 percent. This curve was normalized to a room temperature minimum of 207 MPa (30,000 PSI).

Figure 2.1-2 Yield Strength (Minimum Expected)

APPLICABLE PRODUCT FORMS: The product forms with their room temperature minimums are called out in the graph.

NOTES: These curves are based on tensile tests of uniaxial, solid specimens, performed according to ASTM specifications.

Figure 2.1-3 Total Elongation (Minimum Expected)

Figure 2.1-4 Impact Strength Rockwell Hardness

APPLICABLE PRODUCT FORMS: As called out in the graph.

NOTES: These curves are based on tensile tests of uniaxial, solid specimens, performed according to ASTM specifications.

Figure 2.1-5 Uniform Elongation (Minimum Expected)

APPLICABLE PRODUCT FORMS: All product forms.

NOTES:

Figure 2.1-6 Poisson's Ratio

APPLICABLE PRODUCT FORMS:

NOTES:

Figure 2.1-7 Young's Modulus

APPLICABLE PRODUCT FORMS: All product forms.

NOTES:

Figure 2.1-8 Shear Modulus

2.2 LONG TERM

Figure 2.2-1 Stress to Rupture and Creep

Figure 2.2-1 Stress to Rupture and Creep

3.0 PHYSICAL PROPERTIES

3.1 THERMAL PROPERTIES

- Figure 3.1-1 Specific Heat
- Figure 3.1-2 Thermal Diffusivity
- Figure 3.1-3 Thermal Conductivity
- Figure 3.1-4 Thermal Expansion (Instantaneous)
- Figure 3.1-5 Thermal Expansion (Mean)

APPLICABLE PRODUCT FORMS: All product forms.

NOTES:

Figure 3.1-1 Specific Heat

APPLICABLE PRODUCT FORMS: All product forms.

NOTES:

Figure 3.1-2 Thermal Diffusivity

APPLICABLE PRODUCT FORMS: All product forms.

NOTES:

Figure 3.1-3 Thermal Conductivity

APPLICABLE PRODUCT FORMS: All product forms.

NOTES: The curve represents average behavior.

Figure 3.1-4 Thermal Expansion (Instantaneous)

APPLICABLE PRODUCT FORMS: All product forms.

NOTES: The curve represents average behavior.

Figure 3.1-5 Thermal Expansion (Mean)

3.2 ELECTRICAL/MAGNETIC PROPERTIES

Figure 3.2-1 Electrical Resistivity

Figure 3.2-1 Electrical Resistivity

3.3 MISCELLANEOUS

Figure 3.3-1

Density

APPLICABLE PRODUCT FORMS: All product forms.

NOTES:

Figure 3.3-1 Density

4.0 CHEMICAL PROPERTIES

5.0 NUCLEAR PROPERTIES

6.0 REFERENCES

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SECTION 5.0

NITRONIC 33 (ARMCO 18-3 Mn STAINLESS STEEL)

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3.3	MISCELLANEOUS (Viscosity, Density)

4.0	CHEMICAL PROPERTIES
5.0	NUCLEAR PROPERTIES
6.0	REFERENCES

1.0 BASIC DATA

1.1 GENERAL INFORMATION

Nitronic 33 (Armco 18-3 Mn) is a low-nickel austenitic stainless steel that is better than Type 304 stainless steel in at least five specific areas: (1) Yield strength in the annealed condition is approximately twice that of Type-304; (2) Resistance to stress corrosion cracking is better than Type 304; (3) Low magnetic permeability is retained even after severe cold working; (4) Strength and ductility at cryogenic temperatures are excellent; and (5) Resistance to wear and galling is much superior to the standard austenitic stainless steels.

1.2 COMMERCIAL DESIGNATION

Armco Nitronic 33 is the new name for Armco 18-3 Mn stainless steel.

Armco 18-3 Mn plate, sheet and strip are listed in ASTM Specifications A 240 and A 412 (denoted as Grade XM 29). Application for ASTM specification coverage for Armco 18-3 Mn tubing is currently being processed.

1.2.1 Available Forms

Armco 18-3 Mn Stainless Steel is available in sheet, strip, plate, tubing and extrusions. All products are supplied to standard AISI tolerances.

	%		%
Carbon	0.05 max.	Silicon	1.00 max.
Manganese	11.50/14.50	Chromium	17.00/19.00
Phosphorus	0.060 max.	Nickel	2.25/3.75
Sulfur	0.030 max.	Nitrogen	0.20/0.40

1.4 ROOM TEMPERATURE PROPERTIES (MIN. ACCEPTABLE)

1.4.1 Mechanical Properties

<u>Sheet</u>	<u>Plate</u>	
<u>Tensile</u>	<u>Ultimate Strength</u>	<u>Psi (M Pa)</u>
105,000 (723)	100,000 (689)	

<u>Tensile Yield Strength (0.2%)</u>	<u>Psi (M Pa)</u>
55,000 (379) 55,000 (379)	

<u>Elongation</u>	<u>Percent</u>
40 40	

<u>Reduction of Area</u>	<u>Percent</u>
-	

<u>Modulus of Elasticity</u>	<u>10⁶ Psi</u>

<u>Hardness</u>	<u>Rockwell B</u>
100 max. 100 max.	

1.4.2 Physical Properties

<u>Density at 75°F</u>	<u>ρ</u>	<u>lb/in³ (g/cm³)</u>
	.280 (7.755)	

<u>Specific Heat</u>	<u>c</u>	<u>BTU/H-°F</u>

<u>Thermal Conductivity</u>	k	$\frac{\text{BTU-FT}}{\text{HR-FT}^2 - ^\circ\text{F}}$
<u>Mean Coefficient Lin. Thermal Expansion</u>		$\frac{10^{-6} \text{ in.}}{\text{in.} - ^\circ\text{F}}$
<u>Electrical Resistivity</u>	$\frac{R}{70}$	Microhm - cm

1.4.3 Magnetic Properties

Armco 18-3 Mn Stainless Steel provides very low magnetic permeability even after severe cold working. When cold reduced as much as 70%, its permeability remains below 1.02.

TABLE VII
MAGNETIC PERMEABILITY
ASTM A 324-64, METHOD 4

% Cold Reduction	H = 500	H = 1000
0	1.0014	1.0013
10	1.0013	1.0012
20	1.0015	1.0011
30	1.0010	1.0013
40	1.0015	1.0013
50	1.0011	1.0012
60	1.0012	1.0012
70	1.009	1.0013

1.4.4 Chemical Properties

1.4.5 Nuclear Properties

1.5 SPECIAL CONSIDERATIONS

1.6 PROCESSING

1.7 JOINING

See reference 6.4.

1.8 FORMING

1.9 MACHINABILITY

2.0 MECHANICAL PROPERTIES

2.1 SHORT TERM

Figure 2.1-1 Typical Stress-Strain Curve

Table 2.1-1 Short Time Elevated-Temperature Properties

3.0 PHYSICAL PROPERTIES

3.1 THERMAL PROPERTIES

Table 3.1-1 Thermal Conductivity

Table 3.1-2 Thermal Contraction

Table 3.1-3 Thermal Expansion

3.2 ELECTRICAL/MAGNETIC PROPERTIES

Table 3.2-1 Electrical Resistivity of Elevated Temperature

3.3 MISCELLANEOUS

Typical engineering stress-strain curves for Armco 18-3 Mn and Type 304 bar stock (tested in tension) are shown in Figure 2.1-1. The modulus of elasticity (Young's Modulus) of 18-3 Mn is 28.8×10^6 psi (0.199×10^6 MPa), and Poisson's ratio is 0.295, both measured at room temperature.

Figure 2.1-1 Typical Engineering Stress-Strain Curves Obtained in Tension on Bar Samples (Longitudinal Direction)

TABLE 2.1-1

SHORT-TIME ELEVATED-TEMPERATURE PROPERTIES*

Temperature F (C)	UTS ksi (MPa)	0.2% YS ksi (MPa)	Elong % in 2" (50 mm)
75 (24)	117 (807)	72 (496)	49
200 (93)	106 (731)	59 (407)	50
400 (204)	93 (641)	45 (310)	44
600 (315)	91 (627)	39 (269)	44
800 (426)	82 (565)	36 (248)	49
1000 (538)	74 (510)	32 (221)	39

* Data represent average of eight tests consisting of duplicate longitudinal and transverse tests on each of two heats; both are 0.050" (1.25 mm) thick annealed sheet samples.

3.0 PHYSICAL PROPERTIES

MAGNETIC PERMEABILITY OF NITRONIC 33		
Cold Reduction %	Permeability	
	H = 500	H = 1000
0	1.0014	1.0013
10	1.0013	1.0012
20	1.0015	1.0011
30	1.0010	1.0013
40	1.0015	1.0013
50	1.0011	1.0012
60	1.0012	1.0012
70	1.0009	1.0013

3.1 THERMAL PROPERTIES

3.2 ELECTRICAL/MAGNETIC PROPERTIES

3.3 MISCELLANEOUS

TABLE 3.1-1

THERMAL CONDUCTIVITY AT ELEVATED TEMPERATURES

Temperature		Thermal Conductivity	
F	(C)	Btu/hr/ft ² /in/F	(W/m K)
212	(100)	110	(15.8)
392	(200)	120	(17.3)
572	(300)	131	(18.9)
752	(400)	141	(20.4)
932	(500)	152	(21.9)
1112	(600)	162	(23.4)
1292	(700)	172	(24.8)
1472	(800)	181	(26.1)

TABLE 3.1-2

THERMAL CONTRACTION AT SUB-ZERO TEMPERATURES

Temperature Range		Coefficient of Linear Contraction	
°F	(°C)	L/L per °F	L/L per °C
68 to 0	(20 to -18)	8.33×10^{-6}	(15.00×10^{-6})
68 to -50	(20 to -46)	8.31×10^{-6}	(14.96×10^{-6})
68 to -100	(20 to -73)	8.07×10^{-6}	(14.53×10^{-6})
68 to -150	(20 to -101)	7.61×10^{-6}	(13.70×10^{-6})
68 to -200	(20 to -129)	7.05×10^{-6}	(12.69×10^{-6})
68 to -250	(20 to -157)	6.45×10^{-6}	(11.61×10^{-6})
68 to -300	(20 to -184)	5.86×10^{-6}	(10.55×10^{-6})

TABLE 3.1-3

THERMAL EXPANSION

Temperature Range		Coefficient of Linear Expansion	
F	(C)	in/in/°F	(mm/mm/°C)
78 - 200	(25 - 93)	8.93×10^{-6}	(16.07×10^{-6})
78 - 400	(25 - 204)	9.7×10^{-6}	(16.51×10^{-6})
78 - 600	(25 - 316)	9.68×10^{-6}	(17.42×10^{-6})
78 - 800	(25 - 427)	10.07×10^{-6}	(18.13×10^{-6})
78 - 1000	(25 - 538)	10.43×10^{-6}	(18.77×10^{-6})
78 - 1200	(25 - 649)	10.84×10^{-6}	(19.51×10^{-6})
78 - 1400	(25 - 760)	11.15×10^{-6}	(20.07×10^{-6})
78 - 1600	(25 - 871)	11.40×10^{-6}	(20.52×10^{-6})
78 - 1800	(25 - 981)	11.69×10^{-6}	(21.04×10^{-6})

TABLE 3.2-1

ELECTRICAL RESISTIVITY AT ELEVATED TEMPERATURES

Temperature		Resistivity Microhm - cm
F	C	
77	(25)	74
212	(100)	80
392	(200)	87
572	(300)	94
752	(400)	100
932	(500)	106
1112	(600)	111
1292	(700)	115
1472	(800)	119

4.0 CHEMICAL PROPERTIES

5.0 NUCLEAR PROPERTIES

6.0 REFERENCES

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SECTION 6.0
MOLYBDENUM

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1.0 BASIC DATA

1.1 GENERAL

Molybdenum is a body-centered-cubic refractory metal possessing several attractive mechanical and thermal properties. Among its advantages are high melting temperature, low density, high modulus of elasticity, excellent strength-to-density ratio at elevated temperatures achievable with small alloy additions, and high thermal and electrical conductivity. It has low thermal expansion and relatively low thermal-neutron capture cross-section. It is limited by its poor oxidation resistance at elevated temperatures, poor low temperature ductility, and weld brittleness.

May be made by powder metallurgy techniques and consumable electrode arc casting processes.

1.2 COMMERCIAL DESIGNATIONS

Molybdenum, commercially pure.

AVAILABLE FORMS, SPECIFICATIONS, SUPPLIERS

<u>Forms and Conditions</u>	<u>Specifications</u>
Forgings, stress-relieved	ASTM B-384
Billets	ASTM B-385
Sheet, Strip, Plate and Foil	ASTM B-386
Bar, Rod and Wire	ASTM B-387
Tube	WANL-PDS-30032

1.3 CHEMICAL COMPOSITION (%)

ELEMENT	C	O	N	Fe	Ni	Si	Mo	
MAXIMUM	.040	.003	.001	.020	.010	.010		
MINIMUM	.010						99.9	

SOURCE - ASTM B-384, B-385, B-386 & B-387, Type 1

1.4 ROOM TEMPERATURE PROPERTIES

The room temperature properties in Section 1.4 are averages, except for ultimate tensile strength, tensile yield strength, elongation, and reduction of area, which are 80% of average.

1.4.1 Mechanical Properties

Ductile-brittle transition temperature is near room temperature for most forms.

<u>AS ROLLED</u>		<u>STRESS RELIEVED</u>	<u>RECRYSTALLIZED</u>
Tensile Ultimate Strength		F_{TU}	PSI
Bar	81,000	72,000	54,000
Tensile Yield Strength		F_{TY}	PSI
Bar	63,000	66,000	44,000

<u>Comp. Yield Strength</u>	F_{CY}	<u>PSI</u>
-----------------------------	----------	------------

-	83,000	-
---	--------	---

<u>Ultimate Shear Strength</u>	F_{SU}	<u>PSI</u>
--------------------------------	----------	------------

-	83,000	
---	--------	--

<u>Shear Yield Strength</u>	F_{SY}	<u>PSI</u>
-----------------------------	----------	------------

<u>Ultimate Bearing Strength</u>	F_{BRU}	<u>PSI</u>
----------------------------------	-----------	------------

$e/D = 1.5$

$e/D = 2.0$

<u>Yield Bearing Strength</u>	F_{BRY}	<u>PSI</u>
-------------------------------	-----------	------------

$e/D = 1.5$

$e/D = 2.0$

<u>Elongation</u>	e	<u>%</u>
-------------------	-----	----------

32	33	33
----	----	----

<u>Reduction of Area</u>	RA	<u>%</u>
--------------------------	------	----------

49	55	30
----	----	----

<u>Modulus of Elasticity</u>	E	10^6 <u>PSI</u>
------------------------------	-----	-------------------

Dynamic	46.4
---------	------

Static	47.2
--------	------

<u>Comp. Modulus of Elasticity</u>	E_C	10^6 <u>PSI</u>
------------------------------------	-------	-------------------

<u>Modulus of Rigidity</u>	<u>G</u>	<u>10⁶ PSI</u>
----------------------------	----------	---------------------------

17

Poisson's Ratio

Hardness

Plastic Bending Modulus

1.4.2 Physical Properties

<u>Density</u>	<u>ρ</u>	<u>LB/IN³</u>
----------------	--------------------------	--------------------------

0.369

<u>Specific Heat</u>	<u>C</u>	<u>BTU/LB - °F</u>
----------------------	----------	--------------------

0.059

<u>Thermal Conductivity</u>	<u>k</u>	<u>$\frac{\text{BTU} - \text{FT}}{\text{HR} - \text{FT}^2 - ^\circ\text{F}}$</u>
-----------------------------	----------	---

78.8

<u>Mean Coeff. Lin. Thermal Expans.</u>	<u>α</u>	<u>$\frac{10^{-6} \text{ IN.}}{\text{IN.} - ^\circ\text{F}}$</u>
---	----------------------------	---

(70 - 212°F)

2.70

<u>Electrical Resistivity</u>	<u>R</u>	<u>MICROHM - IN.</u>
-------------------------------	----------	----------------------

2.2

1.4.3 Magnetic Properties

Paramagnetic

Melting Temperature

4730°F

Phase Changes

None

1.4.4 Chemical Properties

Compatibility:

Reacts with oxygen; alloys with tungsten, vanadium, titanium, tantalum, columbium, and chromium in solid solution and iron, nickel, cobalt, aluminum, and silicon, forming a second phase of relatively low alloy content.

Corrosion Resistance:

High resistance to mineral acids and liquid metals, and to water. Corroded by fused alkalis and molten oxidizing salts.

Oxidation Resistance:

MoO₃ begins to sublime above 932°F and at 1110°F volatilization is significant. Existence of molten MoO₃ above 1472°F leads to catastrophic oxidation in ordinary atmospheres.

1.4.5 Nuclear Properties

Irradiation in general increases tensile yield strength and ductile-brittle transition temperature.

1.5 SPECIAL CONSIDERATIONS

Service temperature maximum is 1000°F in oxygen bearing environment.

Must be coated for use in oxidizing atmosphere above 1000°F .

1.6 PROCESSING

Surface Treatment :

Treated by several methods for oxidation resistance and resistance to gall and wear. Clean and degrease by conventional methods.

Thermal Treatment:

Stress relief temperature = $1600 - 1800^{\circ}\text{F}$

Annealing temperature = $1800 - 2200^{\circ}\text{F}$

1.7 JOINING

Can be welded to itself and any material with which it readily alloys by arc, electric resistance, percussion, flash, or electron beam techniques. Welds are of generally poor quality; cast (weld) zone is normally brittle at room temperature. Can also be brazed and mechanically joined. Arc fusion welds of powder, metallurgical grades, generally are brittle and exhibit weld cracking in heavy section joints.

1.8 FORMING

Initial breakdown of the ingot is usually by extruding, with forging at 2150° to 2350°F , and finishing at 1500° to 1700°F .

Can also be formed by spinning, shearing, stamping, punching, hydro forming, bending, and drawing.

1.9 MACHINABILITY

Best with uniform fibrous grain produced with normal amounts of working.

General machinability is comparable to austenitic stainless steels.

2.0 MECHANICAL PROPERTIES (As function of temperature)

2.1 SHORT TERM

2.1.1 Static

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- Figure 2.1-2 Impact Strength Rockwell Hardness
- Figure 2.1-3 Modulus of Elasticity
- Figure 2.1-4 Poisson's Ratio
- Figure 2.1-5 Compressive Strength

MOLYBDENUM

TENSILE STRENGTHS

Figure 2.1-1

MOLYBDENUM **IMPACT STRENGTH** **ROCKWELL HARDNESS**

TEMPERATURES IN 100° F

Figure 2.1-2

11-9

Figure 2.1-3

POISSON'S RATIO

ELECTRICAL RESISTIVITY
MICROHM-IN.

ELECTRICAL RESISTIVITY

Figure 2.1-4

MOLYBDENUM

STRENGTHS COMPRESSIVE, SHEAR, BEARING

61-9

STRENGTH
1000 PSI

Figure 2.1-5

2.2 LONG TERM

Figure 2.2-1 Stress to Rupture and Creep

Figure 2.2-2 Stress vs. Strain

Figure 2.2-3 Stress vs. Strain (Function of Temperatures)

STRESS TO RUPTURE
1000 PSI

Figure 2.2-1

STRESS
1000 PSI

MOLYBDENUM STRESS VS STRAIN

Figure 2.2-2

61-9

MOLYBDENUM

STRESS VS STRAIN AS FUNCTION OF TEMPERATURE

Figure 2.2-3

2.3

CYCLIC LOAD PROPERTIES

Figure 2.3-1 Fatigue Strength

FATIGUE STRENGTH
1000 PSI FATIGUE STRENGTH
1000 PSI

Figure 2.3-1

3.0 PHYSICAL PROPERTIES

3.1 THERMAL PROPERTIES

Figure 3.1-1 Thermal Expansion, Specific Heat and Thermal Conductivity

MEAN COEFFICIENT-LINEAR THERMAL EXPANSION
 10^{-6} IN./IN.-°F

THERMAL EXPANSION VALUES ARE FROM
 ROOM TEMPERATURE TO INDICATED TEMP.

MOLYBDENUM
 THERMAL EXPANSION
 SPECIFIC HEAT

BTU/LB-°F

0.16

0.12

0.08

0.04

0

++ THERMAL EXPANSION, MOLYBDENUM

DATA FROM SEVERAL INVESTIGATORS AND
 FOR SEVERAL REF. TEMPS., TAKEN FROM
 A EXPANSION CURVE AND ADJUSTED TO RT
 REFERENCE. INCLUDES ARC-MELTED
 COMMERCIAL AND HIGH-PURITY MATERIAL.

— SPECIFIC HEAT, MOLYBDENUM

DATA FROM SEVERAL INVESTIGATORS;
 INCLUDES MOSTLY ARC-MELTED,
 COMMERCIAL AND HIGH-PURITY MATERIAL

THERMAL CONDUCTIVITY

THERMAL CONDUCTIVITY
 BTU-FT/HR-FT²-°F

320
280
240
200
160
120
80
40
0

— THERMAL CONDUCTIVITY, MOLYBDENUM

DATA FROM SEVERAL INVESTIGATORS,
 INCLUDES ARC-MELTED, COMMERCIAL
 AND HIGH-PURITY MATERIAL.

..... ESTIMATED TREND

TEMPERATURES IN 100° F

Figure 3.1-1

4.0 CHEMICAL PROPERTIES

5.0 NUCLEAR PROPERTIES

6.0 REFERENCES

- 6.1 Aerospace Structural Metals Handbook, Syracuse University Institute.
- 6.2 Determination of the Tensile Properties Up to 4500°F and the Impact Ductile-Brittle Transition Temperature of Unalloyed Molybdenum Forgings - Southern Research Institute Report 5376 - 1364 XII, June 1962.
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SECTION 7.0
MOLYBDENUM ALLOY - TZM

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3.3	MISCELLANEOUS (Viscosity, Density)

class location

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2.2-2	Stress to Rupture and Creep (Time)
2.2-3	Stress vs. Strain (Temperature)
3.1-1	Thermal Expansion and Conductivity

1.0 BASIC DATA

1.1 GENERAL

TZM Molybdenum alloy is superior in stress-rupture strength and recrystallization temperature to either pure molybdenum or the 0.5 Ti - Molybdenum alloy. Fabricability and machinability are at least equal to Mo or Mo-0.5 Ti.

Values of F_{TU} and F_{TY} are 95% confidence values.

1.2 COMMERCIAL DESIGNATIONS

Molybdenum - 0.5 titanium - 0.08 zirconium alloy.

Available Forms, Specifications, Suppliers

Forms and Conditions	Specifications
Sheet Forging Billets Bars Rolled or Swaged	

Suppliers

1.3 CHEMICAL COMPOSITION (%)

ELEMENT	C	Ti	Zr	H	Fe	Ni	N	O
MAXIMUM	0.04	0.55	0.12	.0005	.010	.002	.002	.0025
MINIMUM	0.01	0.04	0.06	—	—	—	—	

1.4 ROOM TEMPERATURE PROPERTIES
(Average Unless Otherwise Noted)

1.4.1 Mechanical Properties

Sheet, Annealed

Tensile Ultimate Strength	F_{TU}	PSI
	120,000	
Tensile Yield Strength	F_{TY}	PSI
	101,000	
Comp. Yield Strength	F_{CY}	PSI
Shear Strength	F_{SU}	PSI
Ultimate Bearing Strength	F_{BRU}	PSI
Elongation	e	%
	16.0	
Reduction of Area	RA	%
	55.0	
Modulus of Elasticity	E	10^6 PSI
(Static)	45.0	
Modulus of Rigidity	G	10^6 PSI
Comp. Modulus of Elasticity	E_C	10^6 PSI
Plastic Bending Modulus		

1.4.2 Physical Properties

Density	ρ
LB/IN ³	0.369
g/cc	

Specific Heat	C	BTU/LB - °F
(70°F)	0.065	
Thermal Conductivity	k	$\frac{\text{BTU} - \text{FT}}{\text{HR} - \text{FT}^2 - ^\circ\text{F}}$
(212°F)	04.5	
Mean Coeff. Linear Thermal Expansion	α	$\frac{10^{-6} \text{ IN.}}{\text{IN.} - ^\circ\text{F}}$
(70-212°F)	2.7×10^{-6}	
Electrical Resistivity	R	MICROHM - IN.
(70°F)	2.05	

1.4.3 Magnetic Properties

Paramagnetic.

1.4.4 Chemical Properties

This alloy needs protection against oxidation at temperatures above 1000°F, unless the exposure times are very short, or the atmosphere is neutral, reducing, or vacuum. Prolonged exposure to hydrogen above 1000°F can lead to internal hydriding of alloying elements Zr and Ti.

1.4.5 Nuclear Properties

1.5 SPECIAL CONSIDERATIONS

Service Limits

RT to 1000°F in oxidizing atmosphere without surface protection.

1.6 PROCESSING

Surface Treatment

Recrystallization temperature depends on the extent of prior reduction.

Annealing and stress relief must be performed in a neutral or reducing atmosphere.

Stress Relief: 2100° - 2400°F., 15 min. - 1 hr.

Annealing: 2500°F - 2550°F., Hold 1 hr.

This alloy is not hardenable by heat treatment. It can be hardened by mechanical deformation at temperatures below the recrystallization temperature.

1.7 JOINING

This alloy can be fusion and resistance welded. A preheating to 400° to 600°F is recommended. Through chemical cleaning on electroplating of surface to be joined is essential. Fusion welding should be done in an atmosphere free of nitrogen and oxygen.

1.8 FORMING

Sheet and wire up to 0.020 inch in stress-relieved condition can be cold formed by conventional methods. Materials thicker than 0.020 in. should be heated at 200° to 1000°F, depending on section thickness. Preheating of tool is recommended.

Forging, starting temperatures is 2350°F maximum, and finishing temperature is 1900°F minimum.

A GUIDE TO FABRICATION TEMPERATURE FOR TZM ALLOY

1.9 MACHINABILITY

The use of high-speed steel and carbide tools is recommended for this alloy.

Shearing and punching can be performed at 200° to 1000°F.

2.0 MECHANICAL PROPERTIES

2.1 SHORT TERM

2.1.1 Static

Figure 2.1-1 Tensile Strength

2.2 LONG TERM

Figure 2.2-1 Stress to Rupture and Creep (Temperature)

Figure 2.2-2 Stress to Rupture and Creep (Time)

Figure 2.2-3 Stress vs. Strain (Temperature)

TZM
(Mo-0.5Ti-0.08Zr)
MOLYBDENUM ALLOY

TENSILE STRENGTHS

Figure 2.1-1 Tensile Strength

TZM
(Mo-0.5Ti-0.08Zr)
MOLYBDENUM ALLOY

**STRESS TO RUPTURE
AND CREEP
TEMPERATURE**

Figure 2.2-1 Stress to Rupture and Creep (Temperature)

STRESS TO RUPTURE AND CREEP TIME

TZM
(Mo-0.5Ti-0.08Zr)
MOLYBDENUM ALLOY

STRESS VS STRAIN
AS FUNCTION OF
TEMPERATURE

Figure 2.2-3 Stress vs. Strain (Temperature)

3.0 PHYSICAL PROPERTIES

3.1 THERMAL PROPERTIES

Figure 3.1-1 Thermal Expansion and Conductivity

MEAN COEFFICIENT-LINEAR THERMAL EXPANSION
 10^{-6} IN./IN.-°F

THERMAL CONDUCTIVITY
 BTU-FT/HR-FT²-°F

TZM
 (Mo-0.5Ti-0.08Zr)
 MOLYBDENUM ALLOY

THERMAL EXPANSION
 SPECIFIC HEAT

THERMAL EXPANSION VALUES ARE FROM
 ROOM TEMPERATURE TO INDICATED TEMP.

THERMAL CONDUCTIVITY

Figure 3.1-1 Thermal Expansion and Conductivity

4.0 CHEMICAL PROPERTIES

5.0 NUCLEAR PROPERTIES

6.0 REFERENCES

- 6.1 Mechanical Properties of Tungsten and TZM Sheet Produced in the Refractory Metal Sheet Rolling Program, Part II, Contract N600 (19)-59530, Southern Research Institute, 17 Jan. 1966.
- 6.2 The Engineering Properties of Molybdenum and Molybdenum Alloys, DMIC Report, Battelle, September, 1963.
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- 6.6 Determination of the Tensile Properties up to 4500°F and the Impact Ductile - Brittle Transite Temperature of Unalloyed Molybdenum Forgings - Southern Research Institute Report 5376 - 1364 - XII, June, 1962.

SECTION 8.0

TUNGSTEN

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2.1-3	Tensile Strengths
2.1-4	Reduction of Area
2.1-5	Modulus of Elasticity
3.1-1	Thermal Expansion and Conductivity
3.2-1	Electrical Resistivity

1.0 BASIC DATA

1.1 GENERAL

Tungsten is a refractory metal with the highest melting temperature of all of the metals. It is, however, extremely brittle at room temperature, with a ductile-brittle transition temperature of 350°F in the wrought condition and 600°F in the annealed condition. It has body-centered cubic structure, although other forms may exist.

Typical uses are as an alloying element, for electrical and electronic applications, missile and space applications, weights and counter balances in static or dynamic balancing, high-speed rotating inertia members, radiation shielding, and vibration damping.

1.2 COMMERCIAL DESIGNATIONS

Commercially pure tungsten, or commercially pure nonsag tungsten.

Available Forms, Specifications, Suppliers

Forms & Conditions	Specifications
Powder	MIL-T-13827
Wire	MIL-T-14507 ASTM-F-288, AMS-7726
Rod	MIL-T-14507
Billet, Bar, Rod, and Preforms	ASTM-B-410
Plate, Sheet, Strip, and Foil	AMS-7898 AMS-7899
High Density, Sintered or Hot-Pressed	MIL-T-21014

1.3 CHEMICAL COMPOSITION (%)

ELEMENT	W	O ₂	N ₂
MAXIMUM	99 - 99.99% Pure	.005	.010
MINIMUM	-	-	-

1.4 ROOM TEMPERATURE PROPERTIES (F_{tu} , F_{ry} , RA and e are 80% of average; all other properties are average.)

1.4.1 Mechanical Properties

Tensile Ultimate Strength F_{TU} _____ PSI
Comm. Pure Sheet, 0.062-in. SR 166,000

Tensile Yield Strength F_{TY} _____ PSI

Comp. Yield Strength F_{CY} _____ PSI
200,000

Ultimate Shear Strength F_{SU} _____ PSI

Shear Yield Strength F_{SY} _____ PSI

Ultimate Bearing Strength F_{BRU} _____ PSI

$e/D = 1.5$

$e/D = 2.0$

Bearing Yield Strength F_{BRY} _____ PSI

$e/D = 1.5$

$e/D = 2.0$

Elongation	e	%
Sheet, 0.062-In., SR	Longitudinal Transverse	2.4 0.1
Reduction of Area	RA	%
Sheet, SR		< 1
Modulus of Elasticity	E	10 ⁶ PSI
Sheet, 0.062-In.	RT 1830°F	58.5 93
Comp. Modulus of Elasticity	F _C	10 ⁶ PSI
Poisson's Ratio		0.283
Hardness		
Sheet, SR.	45	
Recrystallized	36	

1.4.2 Physical Properties

	<u>Plate</u>	<u>Sheet</u>
Density	ρ	
LB/IN ³	0.697	0.689
g/cc	19.3	19.07
Specific Heat	C	
	0.033	
Thermal Conductivity	k	
	BTU-FT HR-FT ² - °F	
RT	95	
932°F	70	
	8-3	

3630°F

60.5

		$\frac{10^{-6} - \text{IN.}}{\text{IN.} - ^\circ\text{F}}$
Mean Coeff. Lin. Thermal Expan.	α	
RT to 1000°F	2.45	
RT to 3600°F	3.0	
Electrical Resistivity		MICROHM-IN.
		14

1.4.3 Magnetic Properties

Paramagnetic

1.4.4 Chemical Properties

Resists attack by most dilute acids and alkalis at RT, slightly attacked by concentrated acids. Rapidly attacked by hot concentrated acids and alkalis.

Begins to oxide in air at red heat.

Can be used in vacuum and hydrogen to temperatures well above 2000°F.

1.4.5 Nuclear Properties

Few data are available on the effects of radiation on tungsten after exposures of 1×10^{19} NVT (slow) and 5×10^{19} NVT (fast) neutrons. No significant change in the hardness was observed, but the electrical resistivity decreased nearly 40%. The density decreased 0.1-0.15%. After similar exposure a decrease of approximately 22% was observed in the tensile strength of tungsten wire. However, the samples were brittle and difficult to align in the tensile grips and the decrease may not be entirely related to the radiation damage.

1.5 SPECIAL CONSIDERATIONS

Service Limits

In air to 300°F

In vacuum to 3000°F

In hydrogen to 4500°F

Do not use in oxidizing atmospheres

1.6 PROCESSING

Surface Treatment

After forming, either "cold" or "hot", in reducing atmospheres, degrease by conventional methods.

After heating in oxidizing atmosphere, remove oxide coating by momentary immersion in molten caustic soda, followed by drainage, cooling, and rinsing in hot running water.

Thermal Treatment

Sinter in vacuum or hydrogen at 3600° to 5400°F.

Stress-relief anneal from 1100° to 1850°F, depending on time, purity, and degree of cold work.

Heating above 750°F should be done in argon, hydrogen, or dissociated ammonia, except for very thin sheet or wire, protective atmosphere should be used above 500°F.

1.7 JOINING

Welding not recommended because of brittleness. Furnace brazing satisfactory below 3000°F.

1.8 FORMING

Initial forging, rolling, or swaging of sintered compacts at 2900° to 3300°F.

Working temperature ranges from 750°F in the "cold" range to 3000°F in the "hot" range.

Work must be done quickly to overcome the high thermal conductivity and low specific heat.

Use minimum bend radius of $2T$.

1.9 MACHINABILITY

High density forms, whether produced by severe sintering or by mechanical working, are the most difficult of all metals to machine, although they are machinable with proper techniques and tools, fairly good speeds and feeds are recommended; generally, no lubricant is required.

Below 90% of theoretical density, ease of chip removal is inversely related to density. In the extreme of commercial availability, approximately 70% of theoretical density, chips can be removed as readily as from ferritic cast iron.

2.0 MECHANICAL PROPERTIES

(As Function of Temperature)

2.1 SHORT TERM

2.1.1 Static

- Figure 2.1-1 Tensile Strengths
- Figure 2.1-2 Tensile Strengths
- Figure 2.1-3 Tensile Strengths
- Figure 2.1-4 Reduction of Area
- Figure 2.1-5 Modulus of Elasticity

TENSILE STRENGTHS

Figure 2.1-1 Tensile Strengths

TENSILE STRENGTHS

Figure 2.1-2 Tensile Strengths

TENSILE STRENGTHS

Figure 2.1-3 Tensile Strengths

Figure 2.1-4 Reduction of Area

8-12
MODULUS OF ELASTICITY
10⁶ PSI

Figure 2.1-5 Modulus of Elasticity

3.0 PHYSICAL PROPERTIES

3.1 THERMAL PROPERTIES

Figure 3.1-1 Thermal Expansion and Conductivity

Figure 3.1-1 Thermal Expansion and Conductivity

3.2 ELECTRICAL/MAGNETIC PROPERTIES

Figure 3.2-1 Electrical Resistivity

91-8

ELECTRICAL RESISTIVITY
MICROHM-IN.

ELECTRICAL RESISTIVITY

Figure 3.2-1 Electrical Resistivity

4.0 CHEMICAL PROPERTIES

5.0 NUCLEAR PROPERTIES

6.0 REFERENCES

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SECTION 9.0
OXYGEN-FREE COPPER

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4.0	CHEMICAL PROPERTIES
5.0	NUCLEAR PROPERTIES
6.0	REFERENCES

1.0 BASIC DATA

1.1 GENERAL

The outstanding characteristics of OFHC copper are its very high thermal and electrical conductivity, and its resistance to corrosion. It can be formed by most of the methods used for working metals. It is not resistant to sulfur compounds nor to high temperature oxidation. It does resist most atmospheres, ground waters, and sea water. It can be joined by pressure welding and gas-shielded arc welding. It can be soft soldered or silver brazed.

1.2 COMMERCIAL DESIGNATIONS

Oxygen free copper O.F copper, and O.F.H. copper, oxygen-free with Silver.

Available Forms, Specifications, Suppliers

FORMS AND CONDITIONS	SPECIFICATIONS
Flat Products	QQ-C-576 ASTM-B8, B124, B133, B152 (OF), B187 (OF), B272
Rods and Bars	QQ-C-502 ASTM-B12 - (OF), B49, B124, -B133, B187 (OF)
Wire	ASTM-B 1-B2-B3-B33, B189 - B298
Tube	ASTM-B-13 (OF), B68 (OF), B75 (OF), B88, B111, B188 (OF), B280
Pipe	ASTM B42 (OF), B188 (OF)
Shapes	ASTM-B124, -B133, -Bp87 (OF)
Welding Rods	QQ-R-571 CLASS FSRCu-1, MIL-R-19631 TYPE FS-RCu-1

1.3 CHEMICAL COMPOSITION (%)

ELEMENT	Cu
MAXIMUM	
MINIMUM	99.95

SOURCE ASTM B-170

1.4 ROOM TEMPERATURE PROPERTIES

(These properties are averages except for tensile ultimate strength, tensile yield strength, elongation, and reduction of area, which are 82% of average.)

1.4.1 Mechanical Properties

<u>Tensile Ultimate Strength</u>	F_{TU}	<u>PSI</u>
Annealed	25,000	
1/4 Hard	30,000	
1/2 Hard	33,000	
Hard	40,000	
Spring Temper	44,000	
<u>Tensile Yield Strength</u>	F_{TY}	<u>PSI</u>
Anneal	8,000	
1/4 Hard	24,000	
1/2 Hard	26,000	
Hard	36,000	
Spring Temper	40,000	
<u>Comp. Yield Strength</u>	F_{CY}	<u>PSI</u>
<u>Shear Strength</u>	F_{SU}	<u>PSI</u>
<u>Ultimate Bearing Strength</u>	F_{BRU}	<u>PSI</u>

Elongation	e	%
Annealed	45%	
1/4 Hard	25%	
1/2 Hard	14%	
Hard	6%	
Spring Temper	4%	

Reduction of Area	RA	%
-------------------	----	---

Modulus of Elasticity	E	10^6 PSI
	17	

Modulus of Rigidity	G	10^6 PSI
	6.4	

Comp. Modulus of Elasticity E_C		10^6 PSI
-----------------------------------	--	------------

1.4.2 Physical Properties

Density	ρ	LB/IN ³
	0.321 - 0.323	

Specific Gravity	8.89 - 8.94
------------------	-------------

Specific Heat	C	BTU/LB - °F
	0.092	

Thermal Conductivity	k	$\frac{\text{BTU} - \text{FT}}{\text{HR} - \text{FT}^2 - ^\circ\text{F}}$
	226	

Mean Coeff. Lin. Thermal Expans.	α	$\frac{10^{-6} \text{ IN.}}{\text{IN.} - ^\circ\text{F}}$
(32-572°F)	9.3 - 9.8	

Electrical Resistivity	R	MICROHM - IN.
	4.34	

1.4.3 Magnetic Properties

Non-Magnetic

Melting Range

1949° to 1981°F

Phase Changes

None

Thermal Conductivity VS. Temperature

Temperature (°F)	k	$\frac{\text{BTU} - \text{FT}}{\text{HR} - \text{FT}^2 - \text{°F}}$
-100		240
68		226
900		192

Emissivity VS. Temperature

Between 1800°F and 2100°F Emissivity is:

15% of Black Body for 7000 Å Light
25% of Black Body for 6000 Å Light
37% of Black Body for 5500 Å Light
45% of Black Body for 5000 Å Light

1.4.4 Chemical Properties

Copper resists the atmosphere, all natural fresh and salt waters, and alkaline solutions, except those containing ammonium ions. It also resists most organic compounds and all acids except the strong oxidizing acids, such as nitric and concentrated sulfuric acid when boiling. It resists hydrofluoric acid but not hydrochloric acid. It does resist dry chlorine but not wet chlorine.

1.4.5 Nuclear Properties

TBD

1.5 SPECIAL CONSIDERATIONS

Service Limits

Copper is not very strong and the strengthening effect of cold working is removed by annealing at 500°F.

Copper is not resistant to hydrochloric acid, nor is it resistant to wet chlorine. It is not resistant to nitric acid, cold or hot, nor is it resistant to boiling concentrated sulfuric acid. It does not resist high temperature oxidation. Silver is added to copper to increase the softening temperature and the creep resistance. It does not have a marked effect on the electrical conductivity giving a decrease in conductivity of about 0.15% for each ounce-per-ton of silver.

1.6 PROCESSING

Surface Treatment

As a general rule, no surface treatments are applied to copper.

Thermal Treatment

The only thermal treatment effective on copper is annealing after cold working. This reaches completion at temperatures as low as 500°F.

1.7 JOINING

Copper can be joined with the silver brazing alloys, and with the lead tin solders. It can be welded by pressure welding and arc welded using the gas-shielded arc processes. See Reference 3.

1.8 FORMING

Copper is very ductile and can be worked by any desired hot or cold method. Cold reductions of as much as 90% can be accomplished between anneals. See Reference 4.

1.9 MACHINABILITY

Copper machines poorly, having a machinability index 20% of free-cutting brass.

2.0 MECHANICAL PROPERTIES

2.1 SHORT TERM

2.1.1 Static

TENSILE PROPERTIES

Figure 2.1.1-1 Effect of Temperature on Drawing on Room Temperature Tensile Strength of OFHC Copper

Figure 2.1.1-2 Tensile Strengths

Figure 2.1.1-3 True Stress, Strain, Set and Offset Corresponding to Various Yield Strength Criteria

Table 2.1.1-1 Comparative Tensile Properties

Table 2.1.1-2 Effect of Cold Work on Tensile Properties

Table 2.1.1-3 Values of Stress, Strain, Set, and Offset Corresponding to Various Yield Strength Criteria (Ref. 6.9)

MODULUS OF ELASTICITY

Figure 2.1.1-4 Modulus of Elasticity

HARDNESS

Figure 2.1.1-5 Effect of Cold Rolling on Indentation Hardness, Tensile Strength and Elongation of Oxygen Free Copper

Table 2.1.1-4 Vickers Pyramid Hardness

Table 2.1.1-5 Hardness Data

ANNEALING, SOFTENING, RECRYSTALLIZATION

Figure 2.1.1-6 Softening Curves for OFHC copper with Various Amounts of Cold Work

Figure 2.1.1-7 Tensile Strength of OFHC Copper as a Function of Percent Reduction and Temperature on Progressive Annealing

Figure 2.1.1-8 Uniform Elongation of OFHC Copper as a Function of Percent Reduction and Temperature of Exposure Reached on Progressive Annealing

Table 2.1.1-6 Softening Temperatures of OFHC Copper

TENSILE PROPERTIES

Jenkins and Digges (6.6) give the tensile strength and yield strength of OFHC Copper as follows:

Tensile Strength Annealed	31,900 psi
Tensile Strength Cold-drawn 40%	51,100 psi
Yield Strength Annealed	12,200 psi
Yield Strength Cold-drawn 40%	50,300 psi

TABLE 2.1.1-1
Comparative Tensile Properties

Property	Initial Condition	
	Annealed	Cold Drawn 40 Per Cent Reduction
Average grain diameter mm	0.025	—
Average hardness Rockwell F	34	86
Tensile strength 1000 psi	31.9	51.1
Yield strength 1000 psi	12.2	50.3
Per cent elongation in 2 inches at maximum load	39	0.7
Per cent elongation in 2 inches at fracture	51	11
Reduction of area at maximum load	28	0.68
Reduction of area at fracture	88	80

Tensile tests at a rate of extension approximately 1% per-minute.

Benson, McKeown, and Mends (6.7) presented data showing the effect of cold-working on tensile properties of various coppers. The data with tons per square inch converted to psi are in Table 2.1.1.2.

TABLE 2.1.1-2

Effect of Cold Work on Tensile Properties

Copper	Cold Work Per Cent Reduction			
	0	10	25	50
OFHC	0.1% pre-strained (psi)			
	6720	30,200	39,000	47,500
Electrolytic tough pitch	5152	29,800	38,750	45,900
OFHC + silver	6272	30,250	37,630	47,250
Electrolytic tough pitch + silver	6720	30,700	39,200	47,700
OFHC	ultimate tensile strength (psi)			
	32,250	35,170	44,130	47,490
Electrolytic tough pitch	30,900	36,500	45,250	45,920
OFHC + silver	31,580	34,950	44,800	47,260
Electrolytic tough pitch + silver	32,480	35,840	45,000	47,700
OFHC	elongation (per cent)			
	72	44	23	12
Electrolytic tough pitch	68	41	19	14
OFHC + silver	72	52	15	13
Electrolytic tough pitch + silver	65	46	19	12

According to Ellis and Greiner (6.8), there is a marked difference in the tensile properties of OFHC copper when drawn at different temperatures. Figure 2.1.1-3 is adapted from their paper.

Figure 2.1.1-1 Effect of temperature of drawing on room-temperature tensile strength of OFHC copper.

After Ellis and Greiner (Ref. 6.8).

OFHC
COPPER ALLOY

TENSILE STRENGTHS

9-12

TENSILE STRENGTH
1000 PSI

Figure 2.1.1-2

TABLE 2.1.1-3
Values of Stress, Strain, Set, and Offset Corresponding
to Various Yield Strength Criteria (Ref. 6.9)

Copper	0.5 Per Cent Total Strain			0.1 % Perm. Set	0.1 Per Cent Offset		0.2 Per Cent Offset	
	Stress (psi)	Offset (%)	Res. Perm. Set (%)	Stress (psi)	Stress (psi)	Total Strain (%)	Stress (psi)	Total Strain (%)
Electrolytic	46,000	0.229	0.212	44,300	43,700	0.359	45,700	0.473
OFHC	47,000	0.232	0.222	45,000	44,600	0.355	46,800	0.468

Figure 2.1.1-3 True stress-strain curves for tough pitch, OFHC, and OFHC plus silver (Ref. 6.10).

OFHC
COPPER ALLOY

MODULUS OF ELASTICITY

MODULUS OF RIGIDITY

Figure 2.1.1-4

HARDNESS

Table 2.1.1-5 is a compilation of hardness data chiefly from the literature.

The authors of Ref. 6.7 determined the effect of cold-working on hardness. The data are in Table 2.1.1-4.

Thompson (6.12) studied the indentation hardness (and other properties) as affected by cold-working. The direct work reduction (by rolling) was taken far beyond commercial practice. Figure 2.1.1-5 is adapted from the paper.

TABLE 2.1.1-4
Vickers Pyramid Hardness

Cold Work (per cent)	Tough Pitch	OFHC	Tough Pitch + Silver	OFHC + Silver
0	48.0	36.8	44.9	37.8
10	94.1	91.0	96.1	93.4
25	105.0	101.3	105.0	101.0
50	114.5	111.0	116.0	115.0

TABLE 2.1.1-5

Hardness Data

Copper	Shape	Per Cent Work Re- duction	Annealed		Method	Hardness		Reference
			Time (hrs)	Temperature (°C)		Ann.	Hard	
OFHC	Wire	75	2	300	R _F	30	89	+
	Rod	40						
OFHC	Rod	50	1	600	V	40	114	3
Tough Pitch No. 1	Rod	50	1	600	V	40	116	
Tough Pitch No. 2	Rod	50	1	600	V	40	115	
OFHC	Annealed Rod				H _B	42		66
OFHC	Annealed Rod				V	51		
OFHC	Annealed Rod	15			H _B		82	
OFHC	Annealed Rod	15			V		90	
OFHC	Annealed Rod	30			H _B		96	
OFHC	Annealed Rod	30			V		106	
OFHC	Strip	0			V	37		7
OFHC	Strip	10			V		91	
OFHC	Strip	25			V		101	
OFHC	Strip	50			V		111	
OFHC + Ag	Strip	0			V	38		
OFHC + Ag	Strip	10			V		93	
OFHC + Ag	Strip	25			V		102	
OFHC + Ag	Strip	50			V		115	
Tough Pitch	Strip	0			V	48		7
Tough Pitch	Strip	10			V		94	
Tough Pitch	Strip	25			V		105	
Tough Pitch	Strip	50			V		115	

TABLE 2.1.1-5 (Continued)

Hardness Data

Copper	Shape	Per Cent Work Re- duction	Annealed		Method	Hardness		Reference
			Time (hrs)	Temperature (°C)		Ann.	Hard	
Tough Pitch + Ag	Strip *	0			V	45		7
Tough Pitch + Ag	Strip *	10			V		96	
Tough Pitch + Ag	Strip *	25			V		105	
Tough Pitch + Ag	Strip *	50			V		116	
OFHC	Tubing	62.5			R _F		94	15
OFHC	Tubing	90.5			R _F		96	
OFHC + P (Amphos)	Tubing	62.5			R _F		96	
OFHC + P (Amphos)	Tubing	90.5			R _F		96.5	
Phosphorus- Deoxidized	Tubing	62.5			R _F		96	
Phosphorus- Deoxidized	Tubing	90.5			R _F		98.5	

* 1 - 1/4 inch x 0.1 inch

R_F = Rockwell F

V = Vickers

+Data from AMCO Laboratory

Figure 2.1.1-5 Effect of cold rolling on indentation hardness, tensile strength, and elongation of oxygen-free copper.

ANNEALING, SOFTENING, RECRYSTALLIZATION

The response of copper to thermal treatment depends not only on its composition but to a considerable extent on the prior treatment. Thus, for a proper presentation of the results of heating tests, the history of the specimens should be given.

Since 1957, the impurity content of OFHC copper has been materially decreased. This means less contaminating material in solid solution, and therefore softening takes place at a lower temperature than before.

According to tests made by AMCO, the softening temperatures for recent production of OFHC coppers are as shown in Table 2.1.1-6.

TABLE 2.1.1-6
Softening Temperatures of OFHC Copper

Copper	Cold Work	Penultimate Anneal	Temperature 1/2 Softened
OFHC	62	600°C	225°C
OFHC	75	600°C	218°C
OFHC	94	600°C	208°C
OFHC	94	850°C	240°C
OFHC	62	900°C	250°C
Amphos (OFHC + P)	94	600°C	296°C
Electrolytic, tough pitch	94	600°C	218°C

*
For comparison

Figure 2.1.1-6 Softening curves for OFHC copper with various amounts of cold work.

Yokelson and Balicki (6.29) made an extensive study of the work-hardening and reannealing characteristics of five brands of high-conductivity copper, including OFHC, in order to establish the relative thermal stability in the work-hardened condition. They used the spectroscopically pure copper as a standard.

Figure 2.1.1-7 and 2.1.1-8 are reproduced from this paper. They are space-diagrams showing the interrelationship between work-hardening, temperature of anneal, and tensile strength for OFHC copper.

Figure 2.1.1-7 Tensile strength of OFHC copper as a function of per cent reduction and temperature on progressive reannealing. Heating rate employed, 10.8°C per minute.

Figure 2.1.1-8 Uniform elongation of OFHC copper as a function of per cent reduction and temperature of exposure reached on progressive reannealing. Heating rate employed, 10.8°C per minute.

2.1.2 Dynamic

IMPACT

Figure 2.1.2-1 Impact Strength and Reduction of Area

Figure 2.1.2-2 Impact versus Hardness

Table 2.1.2-1 Impact Test Data

OFHC
COPPER ALLOY

IMPACT STRENGTH
ROCKWELL HARDNESS

Figure 2.1.2-1

IMPACT STRENGTH

In all test results found in the literature, the data show a marked superiority for the oxygen-free copper in impact strength. According to Lorig, Dahle, and Roberts (6.12), the addition of phosphorus to OFHC copper causes no change in the impact strength at room temperature and only a small increase at higher temperatures.

Miller (6.13) mentions two papers in which the adverse effect of oxygen on impact strength of copper is indicated.

Rolle, in his discussion of Corson (6.14), cites data showing that phosphorus-deoxidized copper, though stronger than tough pitch, is not quite up to the strength of OFHC copper. It is interesting to note that, according to Rolle, hardening the OFHC and phosphorus-deoxidized coppers results in higher impact values, whereas for the tough-pitch (oxygen-bearing) copper the reverse is indicated.

The data submitted by Rolle are based on the following conditions:

All tests were made on 1/2-inch-square rods of wrought copper. All annealing was at 450°C for 60 minutes, in air. The phosphorized copper that was tested was produced by deoxidation with phosphorus. Impact data are averages of 15 determinations. Two sets of tests were made. Rolle's data are presented in Table 2.1.11 and Figure 2.1.11.

TABLE 2.1.2-1
Impact Test Data

Copper	Tensile Strength (psi)	Reduction of area (per cent)	Elongation in 8 in. (per cent)	Brinell Hardness	Izod Impact Ft-Lb
Hard OFHC	46,000	89	5.0	92	73.2
Hard ETP [*]	48,100	57	4.0	91	35.4
Annealed OFHC	31,900	91.9	43.5	53	54.1
Annealed ETP [*]	32,000	72.5	43.5	54	48.5
Hard OFHC	51,450	88.3	5.0	96	71.7
Hard Phos. ⁺	51,250	78.4	4.8	96	62.2
Annealed OFHC	32,000	91.5	42.0	67	61.3
Annealed Phos. ⁺	33,200	83.7	39.6	69	57.3

* Electrolytic tough pitch

⁺ Phosphorus-deoxidized copper

The data for izod impact, when plotted against Brinell hardness, the two points in each case being connected with a straight line, give results as shown in Figure 2.1.2-2.

Figure 2.1.2-2 Impact Versus Hardness.

2.2 LONG TERM

CREEP AND RUPTURE

Figure 2.2-1

Temperature Stress Limits Curves for
OFHC and OFHC plus Silver, for Various
Creep Rates

Table 2.2-1

Creep Stress Limits

Table 2.2-2

Creep Stress Limits

Table 2.2-3

Creep Stress Limits (Long Duration Tests)

CREEP AND RUPTURE

Many papers have been published on creep and on variations on that theme in which the tests reported were made on OFHC copper.

The following references are pertinent:

Schwoppe, Smith, and Jackson (6.15). The following summary is from this paper:

The effect of cold work on the creep characteristics of tough-pitch and OFHC coppers, unalloyed and silver-bearing, has been determined for temperatures from 200 (93°C) to 572°C. The most important results are:

1. Cold work increases the creep strength of copper; however, the benefit from cold work is lost at temperatures where recrystallization is rapid. This temperature varies with the amount of cold work and the type of copper.
2. The addition of silver to either tough-pitch or OFHC copper raises the temperature at which rapid recrystallization occurs; the effect is approximately the same on both types of copper.
3. While additions of silver effectively lower the creep rate of both tough-pitch and OFHC copper as cold-worked, the silver-bearing OFHC copper has a markedly lower creep rate than comparable tough-pitch copper.

Vosskuhler (6.16). Vosskuhler devoted a great deal of time and effort to correlating the results reported in all the references he had available on the subject of creep in copper

and dilute copper alloys. Thus he put all the data on a common basis, permitting direct comparison. He covered also tests taken to rupture.

Tables 2.2-1, 2.2-2, and 2.2-3 are from Vosskuhler's paper, with kilograms per square millimeter converted to pounds per square inch. In any interpretation of the data it must be noted that there was a considerable variation in the various factors involved in the tests in the various references. Among such variables are preparation, pretreatment, size and shape of specimens, and the method and conditions of the testing.

Vosskuhler assembled all the data available for OFHC and OFHC plus silver, and by plotting on double logarithmic paper derived a relationship between creep rate and temperature which he then plotted linearly. His data have been replotted to show the stresses in pounds per square inch instead of kilograms per square millimeter. The revised curves are shown in Figure 2.2-1.

TABLE 2.2-1

Creep Stress Limits

Data from Reference 6.27

Material	Condition	Temperature		Creep Stress Limit (psi)		
		°C	°F	0.001%	Per 1000 Hrs 0.010%	0.1%
Cu + O ₂	Annealed	150	300	1100	2950	8000
	Grain 0.025 mm	205	400	400	1300	4000
		260	500	100	350	1150
	Drawn 84%	150		5000	9400	14700
		205		1000	2100	4350
	Annealed	150		1600	3600	8200
OFHC	Grain 0.025 mm	205		500	1500	4800
		260		100	400	1700
	Drawn 84%	150			8300	12800
		205		570	1750	5000

TABLE 2.2-2

Creep Stress Limits

Data* from Reference 6.15

Material	Condition	Creep Stress (psi)		Tensile Strength (psi)	Elongation (per cent)
		0.001% per hr	0.01% per hr		
OFHC	Drawn 5%	4300	13,000	33,000	36
	Rolled 5%	4750	14,400	33,100	35
OFHC + Ag 0.054%	Rolled 5%	6000	16,100	33,200	36
	Rolled 20%	2200	12,500	45,500	2
	Rolled 30%	1850	11,800	46,750	3
	Rolled 40%	1850		50,750	2.5
OFHC + Ag 0.076%	Rolled 5%	7150	17,250	33,100	35
Cu + O ₂ 0.063%	Rolled 5%	1750	9,700	36,400	33
	Rolled 20%	1140	7,550	45,400	3.5
	Rolled 30%	1140	7,850	48,800	3
	Rolled 40%	715	6,400	51,000	2.5
Cu + O ₂ + 0.072% Ag	Drawn 5%	6400		38,800	34
	Rolled 5%	2000	11,400	36,000	34

*These data are for short duration tests at 300°C (572°F)

TABLE 2.2-3

Creep Stress Limits

Data from Reference 6.15

(Long Duration Tests)

Material	Condition	Temperature		Creep Stress Limit (psi) 0.01% per 1000 hrs
		°C	°F	
OFHC	Soft	115	240	5,125
	Hard 84.4% Cold Worked	115	240	26,100
	Soft	150	300	3,420
	Hard 84.4%	150	300	8,400
OFHC + Ag 0.051%	Soft	150	300	10,000
Cu + O ₂	Hard 84.4%	100	212	20,000

Figure 2.2-1 Temperature-stress-limit curves for OFHC and OFHC plus silver, for various creep rates.

2.3 CYCLIC LOAD

FATIGUE

Figure 2.3-1

Fatigue Strength

FATIGUE

The usual fatigue procedures do not show a marked difference between oxygen-bearing and oxygen-free coppers. Some papers report a small superiority for the OFHC brand; the real test, however, is in usage, where a real difference in service life in favor of the oxygen-free copper has been manifested.

Anderson and Smith (6.17) tested specimens of 0.300-inch minimum diameter, machined from hard-drawn 0.500-inch-diameter rod, at 3,500 rpm. They report as follows:

OFHC at 300 million cycles: 17,000 psi

Tough pitch at 300 million cycles: 17,000 psi

EFFECT OF ATMOSPHERE

Gough and Sopwith (6.18) found a higher fatigue strength when the "oxygen-free" copper was tested in moisture-free air or in a partial vacuum than in moist air. The difference was 6%. They conclude, ". . . the effect of atmospheric corrosion-fatigue is due to the catalytic agency of water in the presence of oxygen." Compare with Bleakney (6.19) under "Creep," page 36.

OFHC extruded rod, tested in air, showed a fatigue limit of 4.35 ton/sq. in. (9,750 psi), in 30×10^6 cycles. Diameter of the specimen at the thinnest section was 1/2 inch.

Bullen, Head, and Wood (6.20). Quoting from the synopsis:

The X-Ray tests show that when a symmetrical cycle in tension-compression is built up slowly, the grains break down on a widespread scale into disoriented elements. But when the same stress cycle is built up faster than a critical rate the disorientation is largely suppressed. The metallographic evidence indicates that there is a corresponding transition from a wide spread to a highly localized distribution of the deformation zones in the grains.

OFHC
COPPER ALLOY

FATIGUE STRENGTH

Figure 2.3-1

3.0 PHYSICAL PROPERTIES

3.1 THERMAL PROPERTIES

HEAT CONTENT

Figure 3.1-1 Heat Contents of Copper

Figure 3.1-2 Specific Heat

THERMAL EXPANSION

Figure 3.1-3 Thermal Expansion of Copper as Increments
of Length at 0°C.

Figure 3.1-4 Coefficient of Thermal Expansion of Copper

VAPOR PRESSURE

Figure 3.1-5 Vapor Pressure of Copper

Table 3.1-1 Vapor Pressure of OFHC Copper

ELECTRICAL RESISTIVITY

Figure 3.1-6 How Impurities Offset Conductivity in
Pure Copper

Figure 3.1-7 How Cold-Working Affects Conductivity

Figure 3.1-8 Resistivity Versus Temperature

HEAT CONTENT

Kelley, in Bulletin 476, U. S. Bureau of Mines, gives a convenient tabulation of heat content of copper, both crystal and liquid. By conversion of the data, three systems of units were derived which were plotted in Figure 3.1-1.

The curves represent the systems as follows:

Degrees Kelvin:	cal per gram mole
Degrees Centigrade:	cal per gram
Degrees Fahrenheit:	btu per pound

Figure 3.1-1 Heat contents of copper. After data presented by Kelley (Bulletin 476, U. S. Bureau of Mines)

17-6

MEAN COEFFICIENT-LINEAR THERMAL EXPANSION
10⁻⁶ IN./IN.-°F

THERMAL CONDUCTIVITY
BTU-FT/HR-FT²-°F

OFHC
COPPER ALLOY

THERMAL EXPANSION
SPECIFIC HEAT

THERMAL EXPANSION VALUES ARE FROM
ROOM TEMPERATURE TO INDICATED TEMP.

Figure 3.1-2

THERMAL EXPANSION

Since it is probable that no essential difference exists between the thermal expansion of OFHC and the "pure" copper cited in the Metals Handbook (6.21), data calculated from the expression for the length increase with temperature have been used to plot the curve in Figure 3.1-3. The equation is as follows:

$$L_t = L_o [1 + (16.733 t + 0.002626 t^2 + 0.00000091 t^3) \times 10^{-6}]$$

where L_t = length at temperature t °C, L_o = length at 0°C.

Richards (6.22) derived the following equation:

$$L_t = L_o (1 + 1.67 \times 10^{-5} t + 3.8 \times 10^{-9} t^2 + 1.5 \times 10^{-12} t^3)$$

He states that the expansion of the specimen from 0°K to the melting point is 2.78%.

The only paper discovered in the literature covering the determination of thermal expansion of OFHC copper is that of Rubin, Altman, and Johnson (6.23). The data in that article relate to temperatures from 25°K to 295°K (-248° to + 22°C). Figure 3.1-4 is adapted from the paper. The curve agrees well with the one in the Metals Handbook (6.21) for pure copper.

For OFHC copper for temperatures above room temperature, Wilkins and Bunn (6.24) give, per degree Centigrade from 25°C to 300°C, 0.0000177, which is the same as they quote for tough-pitch and for phosphorized copper.

Figure 3.1-3 Thermal expansion of copper as increment of length at 0°C.
After equation for length increase with temperature in
Metals Handbook (6-21)

Figure 3.1-4 Coefficient of thermal expansion of copper.

VAPOR PRESSURE

TABLE 3.1-1
Vapor Pressure of OFHC Copper

Temperature (°K)	Effective Time (sec)	Total Weight Loss (grams)	Effective Area (square centimeters)	Evaporation Rate (g/cm/ sec × 10 ⁸)	Pressure (atmospheres × 10 ⁸)
1143 (870°C)	23,762	0.01949	33.6386	2.438	0.233
1159 (886°C)	23,903	0.03337	33.6825	4.145	0.399
1196 (923°C)	6,566	0.02387	33.7451	10.773	1.054
1241 (968°C)	1,740	0.02261	33.8070	38.437	3.831
1292 (1020°C)	1,947	0.08872	33.8974	134.428	13.672

Edwards, Johnston, and Ditmars (6.25) used OFHC copper for determining the vapor pressures of copper. The data of Table No. III of their paper are given in Table 3.1-3.

Figure 3.1-5 is adapted from this paper, somewhat reduced in size.

Hersh (6.26) developed the following equations for the vapor pressure of solid and liquid copper (brand not identified), respectively:

$$\text{Solid log } P_s = - (1.726 \times 10^4)/T + 9.232$$

$$\text{Liquid log } P_l = - (1.682 \times 10^4)/T + 8.907$$

Figure 3.1-5 Vapor pressure of copper.

ELECTRICAL RESISTIVITY

All commercial coppers are highly refined but they are all allowed a small quantity of impurities under the applicable specifications. Thus, under ASTM B4 and B5, tough pitch wirebars need have a copper content of 99.90% copper and a resistivity of 0.15328 ohm-gram/m², equivalent to 100% IACS and 1.72 microhm-cm. The other 1000 parts per million content are actually not defined. The largest single fraction of the remainder will be oxygen. It serves to tie up many of the impurities as oxides and keep them out of solution. Removed from solution, the impurities have little effect on conductivity.

In the case of OFHC copper, the impurities are in solution and marked attention to the effects of various impurities has been made. There have been a number of investigations of the influence of particular elements on the conductivity of copper. All this data has influenced the care with which OFHC copper is produced and the parameters of major concern are spelled out in the certification supplied for the Certified grade of OFHC brand copper.

The effect of impurities on conductivity of OFHC brand copper is magnified by the fact that the absence of oxygen means that each impurity will have an opportunity to go into solution to the limit of its solid solubility and depress the conductivity. Some elements, like iron and phosphorus, for instance, have much greater effects than others.

Besides the impurity content, several factors influence the resistivity or conductivity of OFHC copper and other high conductivity coppers. These include the amount of cold work, and, conversely, the degree of annealing, the operating temperature and the magnetic environment at cryogenic temperatures.

% BY WEIGHT OF ADDED ELEMENTS

CONDUCTIVITY, % IACS

Figure 3.1-6 How impurities affect conductivity in pure copper

Figure 3.1-7 How cold working affects conductivity

Figure 3.1-8 Resistivity Versus Temperature

3.2 ELECTRICAL/MAGNETIC PROPERTIES

ELECTRICAL CONDUCTIVITY

Figure 3.2.1 Elevated Temperature Electrical Conductivity of OFHC
Copper

Figure 3.2-1 Elevated temperature electrical conductivity of OFHC Copper (Ref. 6.28)

4.0 CHEMICAL PROPERTIES

5.0 NUCLEAR PROPERTIES

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SECTION 10.0
ELECTRICAL COIL INSULATION

TABLE OF CONTENTS

1.0	INSULATION TECHNIQUES
2.0	INSULATION MATERIALS (TENTATIVE)
2.1	REINFORCED PLASTIC
2.2	ELECTRICAL TAPE
2.3	RESIN

1.0 INSULATION TECHNIQUES

1.1 TF Coil Insulation System

1.11 Turn-to-Turn Insulation

Apply two layers of .020" B-stage Scotchply crossplied glass, butt wound, directly over the copper for a total thickness of .040".

The Scotchply will have no pressure sensitive adhesive and the width can be selected to afford the best compromise between optimum winding time and elimination of wrinkling.

1.12 Coil Insulation

Apply an additional two layers of .020" B-stage Scotchply crossplied glass, butt wound, over the entire coil. The Scotchply will have no pressure sensitive adhesive and the width can be selected as above in 1.1

1.13 Pressure Sizing

Size the coil in a suitable pressure mold to provide well controlled dimensions of the final coil. Cure the B-stage resin in the Scotchply while the coil is in the mold, following manufacturer's directions.

1.14 Additional Ground Insulation

After sizing and curing, wrap the entire coil with 15 layers of .002" Mylar tape with no adhesive.

1. 15 Casting Resin

Before assembly of the coil into the structural support, paint by brush the walls and bottom of the structural support with the epoxy casting resin. Pour uniformly one quart of epoxy resin around the bottom of the structural support and then lower the coil into the support ring.

1. 16 Vacuum Impregnation

Using the structural form plus a cover as a vacuum vessel, draw a good (28" or better) vacuum on the coil. While maintaining the vacuum, introduce additional resin from at least 6 equally spaced locations around the cover plate. Maintain vacuum for a minimum of 4 hours.

1. 17 Cure

Remove cover plate. Apply heat to the entire structural form and coil and cure in accordance with resin manufacturer's instructions.

1. 18 Coil Dressing

Apply a straight edge across the walls of the structural ring forcing a quantity of filled epoxy resin ahead of tool to provide a flat level surface on the coil face. The resin can be either room temperature cure or heat curable.

1. 2 EF and OH Coil Insulation System

1. 21 Turn to Turn Insulation

Apply three layers of .0032" polyester tape (Scotch No. 1291 or equal) butt wound over each turn of copper to provide a total thickness of .0096" with the seams of each layer staggered from previous layers.

1.22 Additional Turn to Turn Insulation

Apply three layers of .011" B-stage Scotchply type 1003, unidirectional, (or equal) butt lapped over each conductor to provide an additional thickness of .033".

1.23 Additional Turn to Turn Insulation

Apply an additional three layers as in 1.22.

1.24 Ground Insulation

Apply three layers of .020" B-stage Scotchply unidirectional glass, butt wound, over the entire coil to provide an additional thickness of .060".

1.25 Curing

Provide suitable clamping pressure to the coil and cure the resin tape in accordance with the manufacturer's directions.

2.0 INSULATION MATERIALS (Tentative)

2.1 REINFORCED PLASTIC
SCOTCHPLY TYPE 1002 AND 1003

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1.0 BASIC DATA

1.1 GENERAL

"SCOTCHPLY" Reinforced Plastic Type 1002 is a moldable epoxy-glass laminate designed for production cure cycles. It is recommended for general purpose applications requiring high strength over a temperature range of -60°F to $+250^{\circ}\text{F}$. "SCOTCHPLY" is approved under MIL-P-18177C, MIL-P-25421A and the resin used meets MIL-R-9300A.

1.2 FORMS

The uncured laminate can be supplied in roll or sheet form. Standard filament orientations are unidirectional, crossply, or isotropic. It is possible to order any special filament orientation the application requires. Listed below are the caliper and sizes in which standard orientation rolls are available:

	Average Cured Thickness	Average Uncured Thickness
Unidirectional (one ply)	.010	.011
Crossply (two plies)	.020	.022
Isotropic (three plies)	.030	.033
Widths	-	1/4" to 48"

1.3 SHELF LIFE

Six months minimum at 70°F .

1.4 RESIN CONTENT

36% by weight

1.5 MOLD RELEASE

The caul plates or matched metal die surfaces must be coated with a suitable mold release for epoxy resin laminates. Some satisfactory products are Minnesota Mining and Manufacturing Company's FC-400, Dow Corning's DC-20 and Ram Chemical Corporation's Garan No. 225.

1.6 LINER REMOVAL

Important - The uncured sheets and rolls of "SCOTCHPLY" are protected from foreign matter by a paper liner which must be stripped off prior to molding.

1.7 MOLDING PROCEDURE

With the mold at operating temperature, form the part by gradually closing the mold as the laminate becomes thermoplastic. For maximum laminate density, the mold should be brought into immediate contact with the laminate and the press pressure gradually increased until full pressure is reached one to three minutes before gel. For thin laminates the pressure increase may be more rapid than for thick laminates.

GEL TIME	
TEMPERATURE	GEL TIME
275°F	17 minutes
300°F	9 minutes
325°F	4-1/2 minutes
350°F	2 minutes
375°F	1 minute
400°F	45 seconds

MOLD PRESSURE

25 to 100 psi is recommended. Type 1002 may be vacuum bag molded at 10 to 15 psi with a 10 to 20% reduction in mechanical properties.

1.8 CURE

Two recommended cure cycles are listed in the table below for molding high strength laminates of "SCOTCHPLY" Type 1002. Cure Cycle No. 1 and Cure Cycle No. 2 both produce room temperature mechanical properties as listed in the "Mechanical Properties" table. With the elimination of the oven post-cure in Cure Cycle No. 1 room temperature mechanical properties will be 85% of those values listed. For maximum high temperature properties 300°F post cure should be used with Cycles No. 1 and No. 2.

TABLE

Thickness	CURE CYCLE NO. 1 (press and post cure)		CURE CYCLE NO. 2 (press only)
	Press Time at 330°F	Oven Post Cure at 280°F	Press Time at 330°F
1/8	5 minutes	16 hours	35 minutes
1/4	10 minutes	16 hours	40 minutes
1/2	15 minutes	16 hours	45 minutes
1	25 minutes	16 hours	55 minutes

1.9 GENERAL PROPERTIES

Flammability (inches min.). 0.10
 Barcol Hardness 70
 Rockwell Hardness (M) Scale) 100 - 108
 Specific Gravity 1.8
 Molded Thickness (one ply)010"
 Wet Strength Retention
 (2 Hr. Boil) 86%

2.0 MECHANICAL PROPERTIES

2.1 MECHANICAL PROPERTIES AT VARIOUS ORIENTATIONS

Orientation	Mechanical Property	Temperature °F				
		-60	70	160	250	300
UNIDIRECTIONAL (Stress Angle 0°)	Flexural Strength - PSI $\times 10^3$	192	165	128	80	30
	Modulus in Flexure - PSI $\times 10^6$	5.4	5.3	5.0	4.2	1.0
	Tensile Strength - PSI $\times 10^3$	172	160	139	105	50
	Modulus in Tension - PSI $\times 10^6$		5.7			
	Compression Strength, Edge - PSI $\times 10^3$	115	90	70	45	10

Orientation	Mechanical Property	Temperature °F				
		-60	70	160	250	300
CROSSPLIED (Stress Angle 0° or 90°)	Flexural Strength - PSI $\times 10^3$	137	120	104	75	25
	Modulus in Flexure - PSI $\times 10^6$	3.6	3.5	3.3	2.8	0.8
	Tensile Strength - PSI $\times 10^3$	92	75	62	50	40
	Modulus in Tension - PSI $\times 10^6$		3.7	3.0	2.6	
	Compression Strength, Edge - PSI $\times 10^3$	82	75	66	45	20

Orientation	Mechanical Property	Temperature °F				
		-60	70	160	250	300
ISOTROPIC (Stress Angle 0°, 60° or 120°)	Flexural Strength - PSI × 10 ³	104	80	70	55	16
	Modulus in Flexure - PSI × 10 ⁶	2.8	3.0	2.7	1.8	0.8
	Tensile Strength - PSI × 10 ³	69	57	51	48	36
	Modulus in Tension - PSI × 10 ⁶		2.6	2.3	1.9	
	Compression Strength, Edge - PSI × 10 ³	70	60	52	38	18

2.2 MECHANICAL PROPERTIES AT VARIOUS STRESS ANGLES (AT 70°F)

UNDIRECTIONAL	STRESS ANGLE		
	0°	45°	90°
Flexure Strength - PSI $\times 10^3$	165	20	10
Modulus in Flexure - PSI $\times 10^6$	5.3	2.0	1.6
Tensile Strength - PSI $\times 10^3$	160	3.6	2.9
Modulus in Tensile - PSI $\times 10^6$	5.7	1.4	1.4
Compression Strength, Edge - PSI $\times 10^3$	90	25	20
Izod Impact (Edgewise) (Ft. Lbs./Inch Notch)	60.8	6.8	0.9
*Interlaminar Single Shear Strength - PSI $\times 10^3$	4.3		
CROSSPLIED	STRESS ANGLE		
	0°	45°	90°
Flexure Strength - PSI $\times 10^3$	120	50	120
Modulus in Flexure - PSI $\times 10^6$	3.5	2.0	3.5
Tensile Strength - PSI $\times 10^3$	75	22	75
Modulus in Tensile - PSI $\times 10^6$	3.7	1.6	3.7
Compression Strength, Edge - PSI $\times 10^3$	75	23	75
Izod Impact (Edgewise) (Ft. Lbs./Inch Notch)	35.2	59.2	35.2
*Interlaminar Single Shear Strength - PSI $\times 10^3$	4.1		

*3M test procedure

Flat compression on unit and ply ~ 15,000 - 20,000

ISOTROPIC	STRESS ANGLE		
	0°	45°	90°
Flexure Strength - PSI $\times 10^3$	80	73	79
Modulus in Flexure - PSI $\times 10^6$	3.0	2.8	2.7
Tensile Strength - PSI $\times 10^3$	57	43	43
Modulus in Tensile - PSI $\times 10^6$	2.6	2.9	2.9
Compression Strength, Edge - PSI $\times 10^3$	60	51	51
Izod Impact (Edgewise) - (Ft. Lbs./Inch Notch)	40.8	42.3	38.6
*Interlaminar Single Shear Strength - PSI $\times 10^3$	3.7		

*3M test procedure.

Flat compression on unit and ply ~ 15,000 - 20,000 psi.

3.0 PHYSICAL PROPERTIES

3.1 THERMAL PROPERTIES

THERMAL PROPERTIES COEFFICIENT OF LINEAR EXPANSION

Method - ASTM D696-42T

Tested over Temperature Range of -30°F to $+200^{\circ}\text{F}$

FIBER ORIENTATION	DIRECTION OF MEASUREMENT	COEFFICIENT OF LINEAR EXPANSION PER $^{\circ}\text{F}$
Isotropic	Parallel to one array of filaments	8.4×10^{-6}
Crossplied	Parallel to lengthwise filaments	7.1×10^{-6}
Crossplied	Parallel to crosswise filaments	7.1×10^{-6}
Unidirectional	Parallel to all filaments	4.8×10^{-6}
Unidirectional	Perpendicular to all filaments	12.3×10^{-6}

THERMAL CONDUCTIVITY (k)

$$(k) = \frac{\text{B.t.u. of heat transmitted through 1 inch thickness}}{(^{\circ}\text{F}) \quad (\text{sq. ft.}) \quad (\text{hr.})}$$

Tests conducted on a 1 inch thick isotropic laminate

MEAN TEMPERATURE	THERMAL CONDUCTIVITY (k)
36°F	2.33
45°F	2.32
125°F	2.37
186°F	2.40

Specific Heat = 0.21 Cal/GM-DEG. C

3.2 ELECTRIC/MAGNETIC PROPERTIES

Property	Condi- tioned (at R.H.)	Temp. of Test						
			60	1KC	100KC	1MC	10MC	30MC
Dissipation Factor	50%	23°C	.0052	.006	.014	.017	.016	.023
	50%	60°C		.0087				
	50%	120°C		.0033				
	50%	150°C		.13				
	90%	23°C	.036	.05	.032	.019	.024	.033
	90%	60°C		.054				
Dielectric Constant	50%	23°C	5.3	5.2	5.1	4.8	4.7	4.4
	50%	60°C		5.7				
	50%	120°C		6.1				
	50%	150°C		7.3				
	90%	23°C	7.0	6.5	5.6	5.5	5.1	5.5
	90%	60°C		6.8				
			109V-D.C.					
Volume Resistivity (Ohms-CM)	50%	23°C	4.9×10^{17}					
	90%	23°C	4.9×10^{17}					
Insulation Resistance (Ohms)	50%	23°C	5.3×10^{15}					
	50%	60°C	2.7×10^{14}					
	50%	120°C	6.2×10^{11}					
	50%	150°C	6.8×10^{10}					
	90%	23°C	3.3×10^{14}					
	90%	60°C	9.7×10^{12}					
			Volts/Mil					
Dielectric Strength	50%	23°C	750					
	90%	23°C	635					
					TIME IN SECONDS			
Arc Resistance	50%	23°C			Across Filaments		With Filaments	
	90%	23°C			80		20	
					80		20	

4.0 CHEMICAL PROPERTIES

CROSSPLY (0° - 90°) FIBER ORIENTATION			
Test Method ASTM D543-T43			
7 day immersion at 70° F			
CHEMICAL	PER CENT CHANGE IN WEIGHT	PER CENT CHANGE IN THICKNESS	FLEXURAL STRENGTH PSI × 10 ³
Heptane	+ .02	+ .02	110
Isopropyl Alcohol	+ .16	+ .23	104
Ethylene Glycol	+ .06	+ .02	109
Jet Engine Oil	+ .08	- .14	111
Jet Fuel (JP-4)	+ .07	+ .11	111
Hydraulic Aircraft Oil	+ .07	- .05	114
Sulfuric Acid 3%	+ .06	+ .09	100
Sulfuric Acid 30%	+ .07	+ .24	101
Sodium Hydroxide 1%	+ .19	+ .04	95
Sodium Hydroxide 10%	+ .20	+ .12	94
Hydrogen Peroxide 3%	+ .21	+ .10	110
Distilled Water	+ .17	+ .09	109

5.0 NUCLEAR PROPERTIES

6.0 CURVES

NOTE: CREEP CURVES FROM LAZAN U OF M PROCEDURE.

CREEP
CURVES
Loaded In
Tension
@ 70°F

CREEP
CURVES
Loaded In
Tension
@ 250°F

STRESS RUPTURE Tensile Stress vs. Time to Failure

TENSILE STRESS-STRAIN CURVES

FLEXURAL FATIGUE (SN) CURVES

7.0 REFERENCES

All data from 3M Company Bulletin SP-RSDA (23.5) P. 1. dated May 1, 1969.

Since the manufacturer of the product described in this technical data sheet has no means of controlling the final use of the product by the consumer or user, it is the responsibility of the immediate seller or sellers to inform the user of the purposes for which the product may be fit and suitable and of the properties of the product, including the precautionary measures which must be taken in order to insure the safety of the user and of other third persons and property.

All statements, technical information, and recommendations contained herein are based on tests we believe to be reliable but the accuracy or completeness thereof is not guaranteed, and the following is made in lieu of all warranties, express or implied:

Seller's and manufacturer's only obligations shall be to replace such quantity of the product proved to be defective. Neither seller nor manufacturer shall be liable for any injury, loss or damage, direct or consequential, arising out of the use of or the inability to use the product. Before using, user shall determine the suitability of the product for his intended use, and user assumes all risk and liability whatsoever in connection therewith.

No statement or recommendation not contained herein shall have any force or effect unless in agreement signed by officers of seller and manufacturer.

2.2 ELECTRICAL TAPE
SCOTCH NO. 1291
(POLYESTER FILM WITH ACRYLIC PRESSURE SENSITIVE ADHESIVE)

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1.0 GENERAL

2.0 TYPICAL PROPERTIES

3.0 REFERENCE

1.0 GENERAL

"SCOTCH" Brand Electrical Tape 1291 is a two-mil polyester film with an acrylic pressure sensitive adhesive. It is a single-coated tape featuring an adhesive system which offers resistance to most common cleaning solvents, including Freon¹. The tape also is resistant to mineral oil, hydraulic fluids, etc., when properly cured. The minimum cure cycle for oil resistance is 1 hour at 150°C. The backside of the tape offers excellent printability.

¹Registered Trademark of the DuPont Company

2.0. TYPICAL PROPERTIES

<u>Electrical</u>	<u>Units</u>	<u>Value</u>
Electrical Strength	Volts	6500
Insulation Resistance	Megohms	1×10^6
Electrolytic Corrosion ²	Ratio	1.0
Copper Corrosion ²		None
<u>Physical</u>		
Caliper	Mils (mm)	3.2 (.088)
Tensile Strength	lb./in. (kg./cm.)	50 (8.93)
Elongation	Percent	125
Adhesion to Steel	oz./in. (gm./cm.)	35 (391)

²3M Test Method - Available upon request

3.0 REFERENCES

All data from 3M Company Product Information Bulletin EIP-PI-1291-1 (25.2) R

2.3 RESIN
(Scotchcast 5(XR-5235))

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	<u>Title</u>
1.0	GENERAL
2.0	HANDLING PROPERTIES
3.0	TYPICAL PROPERTIES
4.0	PREPARATION
4.1	MIXING
4.2	DEAERATING
4.3	CASTING AND IMPREGNATING
4.4	STORAGE
4.5	CURING
4.6	HANDLING PRECAUTIONS
5.0	REFERENCES

1.0 GENERAL

General purpose impregnating applications designed to operate at 130°C (Class "B") temperatures are the intended areas of use for our No. 5 Resin. The distinguishing feature of this rigid system is its excellent resistance to moisture. In addition, this transparent resin offers good physical and electrical properties plus low viscosity for maximum impregnating qualities.

2.0 . HANDLING PROPERTIES

MIX RATIO

	Weight	By Weight	By Volume	Initial Viscosity at 23°C (75°F)	Flash Point	Cure Guide	Gel Time
Part A	9.60 lbs./gal. (1.150 kg./litre)	2	63.5%	12,500 cps	232°C (450°F)	at 23°C (75°F) - 24 - 48 hrs.	18 min. at 60°C (140°F)
Part B	8.30 lbs./gal. (.995 Kg./litre)	1	36.5%	100 cps	82°C (180°F)	at 60°C (140°F) - 1 hr.	
Mixed				3,000 cps		at 95°C (203°F) - 1/2 hr.	

3.0 TYPICAL PROPERTIES

PROPERTY	VALUE
Color	Transparent
Specific Gravity	1.14
Hardness (BARCOL)	15
Compressive Strength ¹ (10% Compression)	13,200 PSI (928 Kg./cm ²)
Tensile Strength ² Ultimate	8000 PSI (562 Kg./cm ²)
Elongation ² (% at Break)	7
Flexural Strength ³	12,000 PSI (844 Kg./cm ²)
Thermal Conductivity ⁴ (cal./sec./cm ² , °C/cm)	4.4×10^{-4}
Linear Thermal Expansion ⁴ (length/unit length/°C)	177×10^{-6}
Moisture Absorption ⁴ % Weight increase, 95% RH, 240 Hrs.	.5
Boiling Water (7 days % Weight Gain)	1.8
Hydrolytic Stability ⁵ 120 Days 71°C (160°F) 95% RH Hardness Loss % (Shore D)	1.2
Mechanical Shock, Ball Drop Lbs. ⁴	5
Thermal Aging % Weight Loss 7 days at 105°C 1000 Hrs. at 130°C 1000 Hrs. at 155°C	.44 3.5 6.6
Electrical Strength ⁶ (Volts/Mil) .125" Sample	325
Dielectric Constant ⁷ (1000 Hz 23°C)	3.6
Dissipation Factor ⁷ (1000 Hz 23°C)	.06
Volume Resistivity ⁸ ohm-cm	10^{14}

¹ Federal Std. 406: Method 1021

² Federal Std. 406: Method 1011

³ Federal Std. 406: Method 1031

⁴ MIL-I-16923E

⁵ MIL-I-16923G

⁶ Federal Std. No. 406: Method 4031

⁷ Federal Std. No. 406: Method 4

⁸ Federal Std. No. 406: Method

4.0 PREPARATION

4.1 MIXING

Mix the separate parts before removing them from their containers. They may be warmed to 60°C. (140°F) to aid mixing. (Gel time is approximately 20 minutes at 60°C. Thoroughly mix together part A and B in the correct proportions. Mix until the color is uniform or a homogeneous mixture is obtained.

4.2 DEAERATING

Air introduced during mixing can be removed by evacuating at 5 to 10 mm of mercury absolute pressure. The resin can be warmed to aid air removal. Container side wall should be four times high of liquid resin to contain the foaming that takes place under vacuum.

4.3 CASTING AND IMPREGNATING

Pour the warm resin into the preheated (100°C.) mold. If no mold is used, dip the preheated part into the resin. Heating the part, resin and mold aids impregnation. For maximum impregnation, evacuate at 5 mm of mercury absolute pressure, or pour under vacuum and hold for several minutes before releasing.

4.4 STORAGE

This resin system has a minimum shelf life of one year. Both parts should be stored in a cool, dry place. When not in use, containers should be kept tightly closed.

4.5 CURING

The resin will cure at room temperature in 24 to 48 hours. Maximum properties can be achieved more quickly by allowing the resin to gel for 2 to 4 hours at 140°F. Thin resin sections can be cured in 2 to 4 hours at 140°F. Castings, which require a large mass of resin,

should be poured in several layers to minimize the temperature rise due to exotherm. The heat produced by a large mass of this resin might otherwise cause the hardener to volatilize leaving bubbles in the casting. The resin cures to a transparent yellow.

4.6 HANDLING PRECAUTIONS

Many of the reactive materials used with epoxy resins have been reported to cause skin irritation to sensitive persons. The user is cautioned to avoid contact with the resin and hardener. The use of protective clothing is recommended. If contact occurs, the skin should be washed immediately with mild soap and water. In case of eye contact, flush immediately with water and secure medical attention. Use only in well-ventilated areas and avoid prolonged or repeated breathing of vapors.

5.0 REFERENCES

All of the information is from 3-M Products Information Bulletin EIP-RPI-5235 (34.2)R.

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No statement or recommendation not contained shall have any force or effect unless in an agreement signed by officers of seller and manufacturer.