UNCLASSIFIED

AD 426255

DEFENSE DOCUMENTATION CENTER

FOR

SCIENTIFIC AND TECHNICAL INFORMATION

CAMERON STATION, ALEXANDRIA, VIRGINIA

UNCLASSIFIED

NOTICE: When government or other drawings, specifications or other data are used for any purpose other than in connection with a definitely related government procurement operation, the U. S. Government thereby incurs no responsibility, nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use or sell any patented invention that may in any way be related thereto.

DDC 42256

DMIC Report 188
September 6, 1963

THE ENGINEERING PROPERTIES OF COLUMBIUM AND COLUMBIUM ALLOYS

DEFENSE METALS INFORMATION CENTER
Battelle Memorial Institute
Columbus 1, Ohio

The Defense Metals Information Center was established at Battelle Memorial Institute at the request of the Office of the Director of Defense Research and Engineering to provide Government contractors and their suppliers technical assistance and information on titanium, beryllium, magnesium, refractory metals, high-strength alloys for high-temperature service, corrosion- and oxidation-resistant coatings, and thermal-protection systems. Its functions, under the direction of the Office of the Secretary of Defense, are as follows:

1. To collect, store, and disseminate technical information on the current status of research and development of the above materials.

2. To supplement established Service activities in providing technical advisory services to producers, melters, and fabricators of the above materials, and to designers and fabricators of military equipment containing these materials.

3. To assist the Government agencies and their contractors in developing technical data required for preparation of specifications for the above materials.

4. On assignment, to conduct surveys, or laboratory research investigations, mainly of a short-range nature, as required, to ascertain causes of troubles encountered by fabricators, or to fill minor gaps in established research programs.

Contract No. AF 33(616)-7747
Project No. 2(8-8975)

"The information in this report came from many sources, and the original language may have been extensively quoted. Quotations should credit the primary authors and the originating agency. Where intent questions appear to be involved, the usual preliminary search is advised before making use of the material, and where copyrighted material is used, permission should be obtained for its further publication."

DMIC Report 188
September 6, 1963

THE ENGINEERING PROPERTIES OF COLUMBIUM AND COLUMBIUM ALLOYS

by

F. F. Schmidt and H. R. Ogden

to

OFFICE OF THE DIRECTOR OF DEFENSE
RESEARCH AND ENGINEERING

DEFENSE METALS INFORMATION CENTER
Battelle Memorial Institute
Columbus 1, Ohio

FOREWORD

The growing interest in the use of columbium, molybdenum, tantalum, and tungsten metals and their alloys for structural applications has emphasized the need for an up-to-date review of some of the more important physical, mechanical, and metallurgical properties of these materials. Four consecutively numbered reports covering columbium and columbium alloys, molybdenum and molybdenum alloys, tantalum and tantalum alloys, and tungsten and tungsten alloys have been prepared. The intent of these reports has been to assemble, present, and summarize, in easy reference form, the engineering-property data of these four refractory metals and alloys. This report covers columbium and columbium alloys.

In addition to data available from the published literature, numerous organizations have contributed data for inclusion in this report. The Defense Metals Information Center gratefully acknowledges the assistance of the following individuals and organizations who contributed valuable information used in the preparation of this report.

G. D. McArdle and F. Nair, Climax Molybdenum Company
H. Peters, E. I. du Pont de Nemours Company, Inc.
R. L. Wilkey, Fansteel Metallurgical Corporation
R. Bancroft and M. Schussler, Haynes Stellite Company
R. W. Werner, Lawrence Radiation Laboratory
G. P. Trost, Metals and Controls, Inc.
M. Torti, National Research Corporation
W. Bauer, Stauffer Metals Company
R. B. Bargainnier, Sylvania Electric Products, Inc.
C. Mueller and G. A. Liadis, Universal Cyclops Steel Corporation
S. A. Worcester, Wah Chang Corporation
R. L. Ammon, R. T. Begley, and H. G. Sell, Westinghouse Electric Corporation

TABLE OF CONTENTS

	Page
SUMMARY	1
INTRODUCTION	3
ORGANIZATION OF DATA PRESENTED IN THE APPENDIX	5
APPENDIX	
COLUMBIUM AND COLUMBIUM ALLOYS	A-1
Unalloyed Columbium	A-1
Cb-1Zr	A-39
Cb-5Zr	A-51
Cb-5V	A-59
Cb-10Hf-1Ti-0.5Zr	A-65
Cb-10Ta-10W	A-71
Cb-28Ta-10W-1Zr	A-79
Cb-33Ta-1Zr	A-91
Cb-10Ti-5Zr	A-105
Cb-10Ti-10Mo-0.1C	A-115
Cb-5W-1Zr	A-129
Cb-10W-1Zr-0.1C	A-135
Cb-10W-2.5Zr	A-143
Cb-10W-10Hf	A-163
Cb-15W-5Mo-1Zr	A-173
Cb-15W-5Mo-5Ti-1Zr	A-209
Cb-20W-1Zr	A-215
Cb-20W-10Ti-6Mo	A-221
Cb-5V-5Mo-1Zr	A-229

THE ENGINEERING PROPERTIES OF COLUMBIUM AND COLUMBIUM ALLOYS

SUMMARY

This report presents the results of a state-of-the-art survey covering columbium and 18 of its most promising alloys. All data are given in tabular and graphical form covering some of the more important physical, mechanical, and metallurgical properties for each material. References are given at the conclusion of each material section.

INTRODUCTION

The requirements for structural materials for service temperatures in excess of those attainable with present materials of construction has provided the stimulus for the development of refractory metals and alloys. Interest has stemmed largely from the high-temperature structural-engineering requirements associated with military hardware. In the development of the refractory metals columbium, molybdenum, tantalum, and tungsten and their alloys, extensive studies have been conducted and are in progress which are aimed toward the investigation of fundamental metallurgical concepts, alloy development, pilot scale-up development of promising compositions, and, ultimately, alloy commercialization.

This report reviews some of the more important properties of columbium and 18 of its alloys. Of this group of alloys, several have not reached true commercial status; however the potential of these advanced experimental and pilot-production alloys warrants consideration. All data are presented in tabular and graphical form according to a number of important physical, mechanical, and metallurgical properties for columbium and each of its 18 alloys. Properties and alloys covered in this report are listed in Table 1.

Intensive laboratory studies on columbium alloys over the past decade have resulted in the continual evaluation of pilot quantities of a large number of promising alloys. The present trend of alloy development is directed toward refinement rather than toward new basic compositions. A significant amount of work is being conducted in the area of fabrication, solution treating, and aging.

In preparing this state-of-the-art survey, technical journals and publications, research reports, and trade literature made available to the Defense Metals Information Center were supplemented with personal contacts with a number of individuals and organizations actively engaged in the refractory-metals field. References are given at the conclusion of each material section.

TABLE 1. ALLOYS AND PROPERTY DATA COVERED IN THIS REPORT

Alloy Composition	Identification of Material	Designation	Chemical Composition	Forms Available	Physical Properties	Melting Point	Density	Thermal Expansion	Thermal Conductivity	Electrical Resistivity	Mechanical Properties	Tensile Properties	Ultimate Tensile Strength	Tensile Yield Strength	Elongation	Reduction in Area	Modulus of Elasticity	Notched Tensile Properties	Creep and Stress-Rupture Properties	Other Selected Mechanical Properties	Metallurgical Properties	Fabricability	Transition Temperature	Weldability	Stress-Relief Temperature	Recrystallization Temperature
Columbium		x	x	x		x	x	x	x	x			x	x	x	x	x	x	x	x		x	x	x	x	x
Cb-1Zr		x	x	x		x	x						x	x	x	x	x		x	x		x		x	x	x
Cb-5Zr		x	x	x		x	x	x					x	x	x	x	x		x			x	x	x	x	
Cb-5V		x	x	x		x	x	x		x			x	x	x		x		x	x		x	x	x	x	x
Cb-10Hf-1Ti-0.5Zr		x	x	x			x						x	x	x		x			x		x	x	x	x	x
Cb-10Ta-10W		x	x	x		x	x						x	x	x	x			x	x		x	x	x	x	x
Cb-28Ta-10W-1Zr		x	x	x		x	x	x	x				x	x	x	x	x	x	x	x		x	x	x	x	x
Cb-23Ta-1Zr		x	x	x		x	x	x					x	x	x		x	x	x	x		x	x	x	x	x
Cb-10Ti-5Zr		x	x	x		x	x	x	x				x	x	x	x	x		x			x	x	x		
Cb-10Ti-10Mo-0.1C		x	x	x		x	x	x	x				x	x	x	x	x		x	x		x	x	x		x
Cb-5W-1Zr		x	x	x			x						x	x	x				x	x		x	x	x	x	x
Cb-10W-1Zr-0.1C		x	x	x		x	x						x	x	x	x			x	x		x	x	x	x	x
Cb-10W-2.5Zr		x	x	x			x	x	x				x	x	x	x	x	x	x	x		x	x	x	x	x
Cb-10W-10Hf		x	x	x			x						x	x	x		x		x	x		x	x	x	x	x
Cb-15W-5Mo-1Zr		x	x	x		x	x	x	x				x	x	x	x	x	x	x	x		x	x		x	x
Cb-15W-5Mo-5Ti-1Zr		x	x	x		x	x	x	x				x	x	x		x		x			x	x		x	x
Cb-20W-1Zr		x	x	x			x						x	x	x	x			x			x	x		x	
Cb-20W-10Ti-6Mo		x	x	x			x						x	x	x	x			x			x	x			x
Cb-5V-5Mo-1Zr		x	x	x		x	x	x		x			x	x	x	x	x		x	x		x	x	x	x	x

ORGANIZATION OF DATA PRESENTED IN THE APPENDIX

1. Identification of Material

    Designation
    Chemical composition
    Forms available

2. Physical Properties

    Melting point
    Density
    Thermal expansion
    Thermal conductivity
    Electrical resistivity

3. Mechanical Properties

    Tensile Properties at Room Temperature

        Ultimate tensile strength
        Tensile yield strength
        Elongation
        Reduction in area
        Modulus of elasticity

    Effect of Temperature on Tensile Properties

        Ultimate tensile strength
        Tensile yield strength
        Elongation
        Reduction in area
        Modulus of elasticity

    Notched Tensile Properties

    Creep and Stress-Rupture Properties

    Other Selected Mechanical Properties

4. Metallurgical Properties

    Fabricability
    Transition temperature
    Weldability
    Stress-relief temperature
    Recrystallization temperature

References

APPENDIX

COLUMBIUM AND ITS ALLOYS

APPENDIX

COLUMBIUM AND ITS ALLOYS

Unalloyed Columbium

1. Identification of Material

   a. Designation: many, depending upon individual supplier

   b. Chemical composition: Tables A-1 and A-2

   c. Forms available: ingot, strip, sheet, foil, plate, bar, rod, wire, and tube[1-4]

TABLE A-1. CHEMICAL REQUIREMENTS FOR COLUMBIUM PRODUCED BY FUSION, POWDER METALLURGY, OR OTHER SUITABLE MEANS TO PRODUCE CONSOLIDATED METAL FOR PROCESSING TO VARIOUS BASIC SHAPES[a](1-4)

Element		Content, Maximum, ppm		
		Reactor Grade		Commercial Grade
C	Each ingot	100	Each ingot	500
N		300		400
O		300		800
H		20		50
Zr		500		1000
Fe		500		500
Ta		1000		2000
Ti		500		500
Si		300		500
B		2		--
W	When so specified	500	When so specified	500
Mo		500		500
Al		100		500
Be		100		--
Cd		5		--
Cr		100		500
Co		30		--
Cu		100		--
Pb		50		--
Li		10		--
Mg		50		--
Mn		100		500
Ni		200		500
Sn		200		500
V		200		500
Y		10		--
Zn		50		--
U		2		--
Hf		100		--
Ca		100		--
Na		100		--
Cl		300		--
Cb, by difference		99.6% min		99.2% min

(a) For ingot, strip, sheet, foil, plate, bar, rod, wire, and tube.

TABLE A-2. REPRESENTATIVE ANALYSES OF COLUMBIUM AS PRODUCED BY POWDER METALLURGY AND ELECTRON-BEAM PROCESSES[a]

Impurity Element	Powder Metallurgy[5]	Electron-Beam Melted			
		Ref. (6)	Ref. (7)	Ref. (8)	Ref. (9)
C	50	30	<30	40	50
O	500	40	62	150	60
N	100	90	44	50	48
H	1	15	--	--	<2
Al	20	--	--	<20	<20
B	--	--	--	<1	<1
Cd	--	--	--	<1	<5
Cr	--	--	--	<20	<20
Cu	30	--	<40	<40	<40
Fe	30	--	<100	<100	<100
Hf	--	--	--	--	<80
Mg	<10	--	--	<20	<20
Mn	10	--	--	<20	<20
Mo	100	--	--	<20	<20
Ni	60	--	--	<20	<20
Pb	--	--	--	<20	<20
Si	100	--	<100	<100	<100
Sn	--	--	--	<20	<20
Ta	--	500	390	1800	<500
Ti	20	--	<150	<150	<150
V	--	--	--	<20	<20
W	--	--	<300	400	<300
Zn	--	--	--	<20	<20
Zr	100-6000	--	--	--	<500
Others	--	100	<20	--	--

(a) Analyses are given in parts per million.

TABLE A-2. REPRESENTATIVE ANALYSES OF COLUMBIUM AS PRODUCED BY POWDER METALLURGY AND ELECTRON-BEAM PROCESSES[a]

Impurity Element	Powder Metallurgy[b]	Electron-Beam Melted			
		Ref. (6)	Ref. (7)	Ref. (8)	Ref. (9)
C	50	30	<30	40	50
O	500	40	62	150	60
N	100	90	44	50	48
H	1	15	--	--	<2
Al	20	--	--	<20	<20
B	--	--	--	<1	<1
Cd	--	--	--	<1	<5
Cr	--	--	--	<20	<20
Cu	30	--	<40	<40	<40
Fe	30	--	<100	<100	<100
Hf	--	--	--	--	<80
Mg	<10	--	--	<20	<20
Mn	10	--	--	<20	<20
Mo	100	--	--	<20	<20
Ni	60	--	--	<20	<20
Pb	--	--	--	<20	<20
Si	100	--	<100	<100	<100
Sn	--	--	--	<20	<20
Ta	--	500	390	1800	<500
Ti	20	--	<150	<150	<150
V	--	--	--	<20	<20
W	--	--	<300	400	<300
Zn	--	--	--	<20	<20
Zr	100-6000	--	--	--	<500
Others	--	100	<20	--	--

(a) Analyses are given in parts per million.

2. Physical Properties

   a. Melting point: 4475 F[10]

   b. Density: 0.310 lb/in.^{3}[10]

   c. Thermal expansion: Table A-3 and Figure A-1

   d. Thermal conductivity: Figures A-2 and A-3

   e. Electrical resistivity: Figures A-4 through A-6

TABLE A-3. THERMAL EXPANSION OF COLUMBIUM[11]

Temperature		Coefficient of Thermal Expansion[a]			
		Average[b]		Instant[c]	
C	F	10^{-6}/C	10^{-6}/F	10^{-6}/C	10^{-6}/F
300	570	7.31	4.06	7.38	4.10
400	750	7.39	4.10	7.54	4.19
500	930	7.47	4.15	7.61	4.23
600	1110	7.56	4.20	7.87	4.37
700	1290	7.64	4.24	8.03	4.46
800	1470	7.72	4.29	8.20	4.55
900	1650	7.80	4.33	8.37	4.65
1000	1830	7.88	4.38	8.52	4.73

(a) Equation for linear thermal expansion: $L = L_0 [1 + 6.892 \times 10^{-6}T + 8.17 \times 10^{-10}T^2]$, T in deg C.
(b) Mean values between 20 C (70 F) and temperature indicated.
(c) Instantaneous values at temperature indicated.

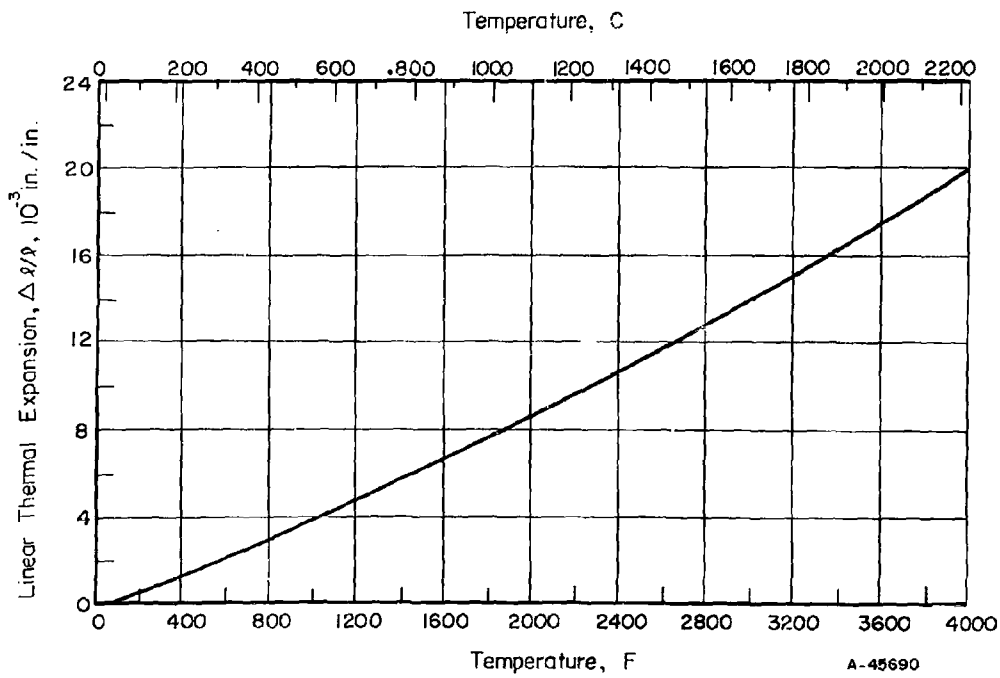


FIGURE A-1. THERMAL EXPANSION OF COLUMBIUM FROM ROOM TEMPERATURE TO 4000 F[12]

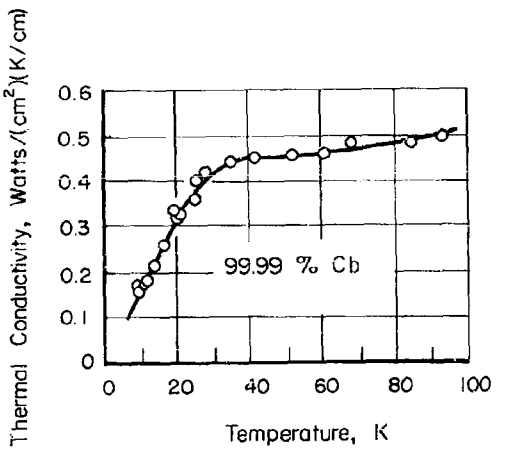


FIGURE A-2. THERMAL CONDUCTIVITY OF COLUMBIUM AT LOW TEMPERATURES[13]

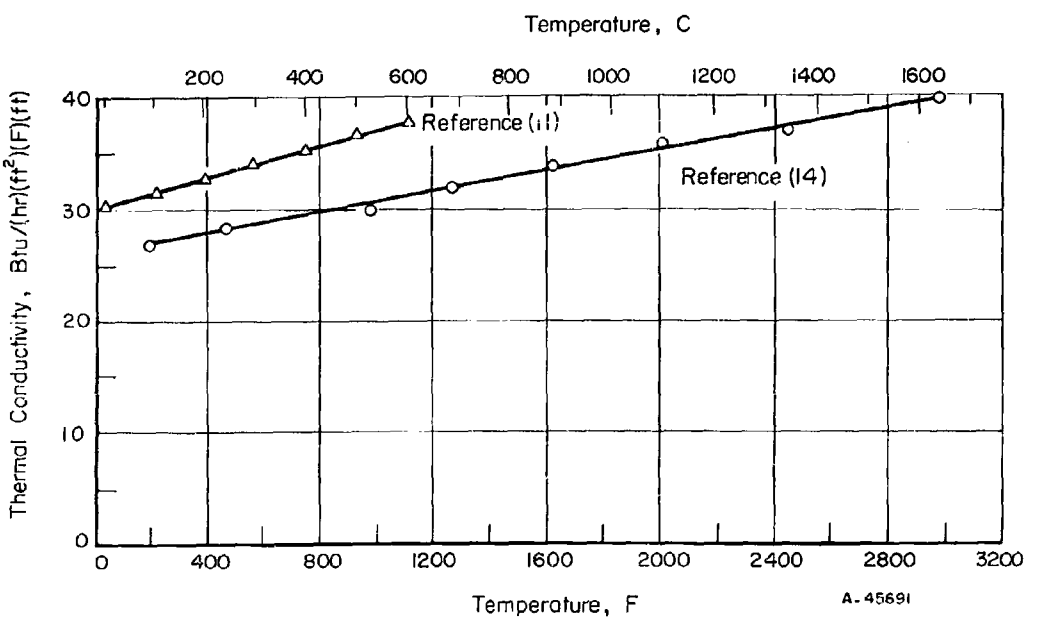


FIGURE A-3. THERMAL CONDUCTIVITY OF COLUMBIUM FROM ROOM TEMPERATURE TO 3000 F

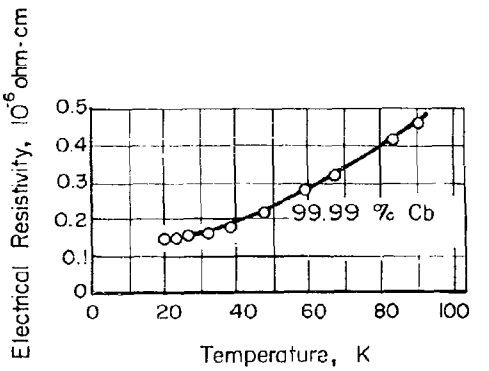


FIGURE A-4. ELECTRICAL RESISTIVITY OF COLUMBIUM AT LOW TEMPERATURES[13]

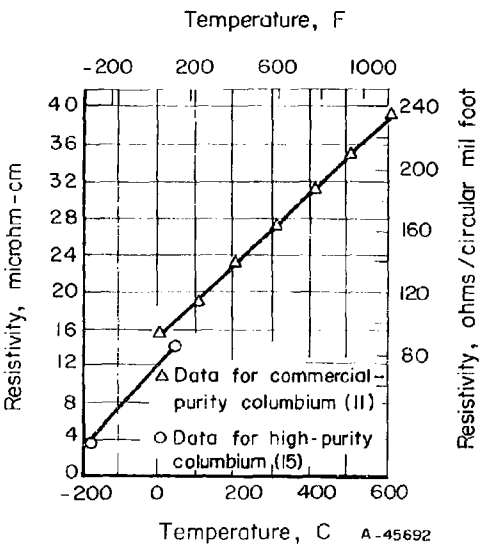


FIGURE A-5. ELECTRICAL RESISTIVITY OF COLUMBIUM

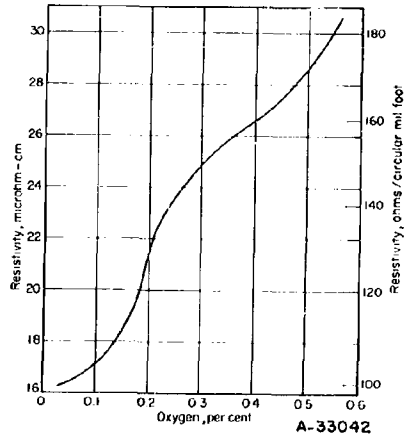


FIGURE A-6. EFFECT OF OXYGEN ON THE ELECTRICAL RESISTIVITY OF COLUMBIUM AT ROOM TEMPERATURE[11]

3. Mechanical Properties

a. Tensile Properties at Room Temperature

Ultimate tensile strength: Tables A-4 and A-5
Figures A-7 through A-10

Tensile yield strength: Tables A-4 and A-5
Figure A-9

Elongation: Tables A-4 and A-5
Figures A-7 through A-10

Reduction in area: Table A-5

Modulus of elasticity: 15×10^6 psi[10]

b. Effect of Temperature on Tensile Properties

Ultimate tensile strength: Table A-6
Figures A-11 through A-17

Tensile yield strength: Figure A-11

Elongation: Table A-6
Figures A-11 and A-12

Reduction in area: Figure A-11

Modulus of elasticity: Table A-6
Figure A-17

c. Notched Tensile Properties

Figures A-18 through A-25

d. Creep and Stress-Rupture Properties

Tables A-7 and A-8
Figures A-26 through A-28

e. Other Selected Mechanical Properties

Hardness: Tables A-9 through A-11
Figure A-29

Impact: Figures A-30 and A-31

Fatigue: Figure A-32

TABLE A-4. TENSILE PROPERTY REQUIREMENTS FOR REACTOR GRADE AND COMMERCIAL GRADE COLUMBIUM PRODUCTS[a](2-4)

Grade	Maximum Tensile Strength, 1000 psi	Maximum Yield Strength (0.2% Offset), 1000 psi	Minimum Elongation in 1 Inch[b], per cent
Reactor	65	55	15
Commercial	85	75	8

(a) For strip, sheet, foil, plate, bar, rod, wire, and tube. Properties for stress-relieved material (1600 F minimum) tested at 0.002 to 0.005 inch per inch per minute through 0.6 per cent offset, and 0.02 to 0.05 inch per inch per minute to fracture.

(b) Elongation for tube products to be in 2 inches.

TABLE A-5. SOME SELECTED ROOM-TEMPERATURE TENSILE PROPERTIES OF COLUMBIUM

Condition	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent	Reference
Annealed sheet (1 hr 2200 F, 0.020 inch)[a]	52.8	37.1	26	--	(16)
Cold-worked sheet (0.125 inch)	80-100	--	5-15	--	(17)
Annealed sheet (0.125 inch)	45-55	--	15-40	--	(17)
Annealed sheet[b]	35	25	40	--	(6)
Cold-rolled sheet (97%, 0.004 inch)[c]	84	--	5	--	(18)
Annealed sheet (97%, 1/2 hr 2010 F, 0.004 inch)[c]	19.5	--	19	--	(18)
Annealed bar (1 hr 2200 F, 3/8 inch)[a]	41.6	28.5	45	--	(16)
As extruded tubing (reduced 86% at 800 F)	64.4	62.2	9	--	(5)
Wrought material[d]	85	--	5	--	(10)
Annealed material[d]	40	30	30	80	(10)

(a) Typical analyses 0.0080% C, >0.0100% N, 0.0100% O, and 0.0005% H.

(b) Electron-beam melted. Typical analyses 99.9% Cb, 0.0030% C, 0.0040% O, 0.0090% N, 0.0015% H, 0.0500% Ta, and 0.0100% others.

(c) 9.92% Cb.

(d) 0.0100 to 0.0200% interstitial contaminants.

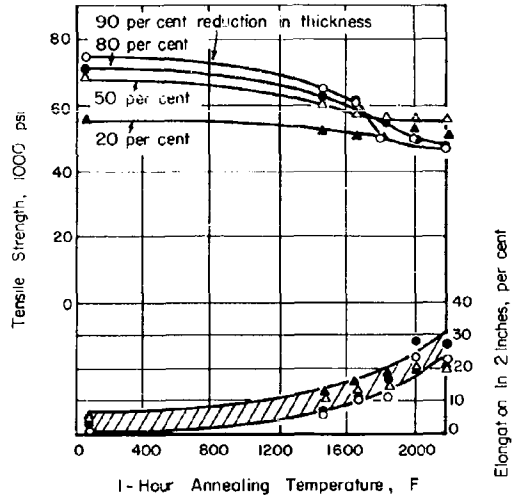


FIGURE A-7. ROOM-TEMPERATURE TENSILE PROPERTIES OF COMMERCIALLY PURE ARC-CAST COLUMBIUM AS A FUNCTION OF DEFORMATION AND ANNEALING TEMPERATURE[19]

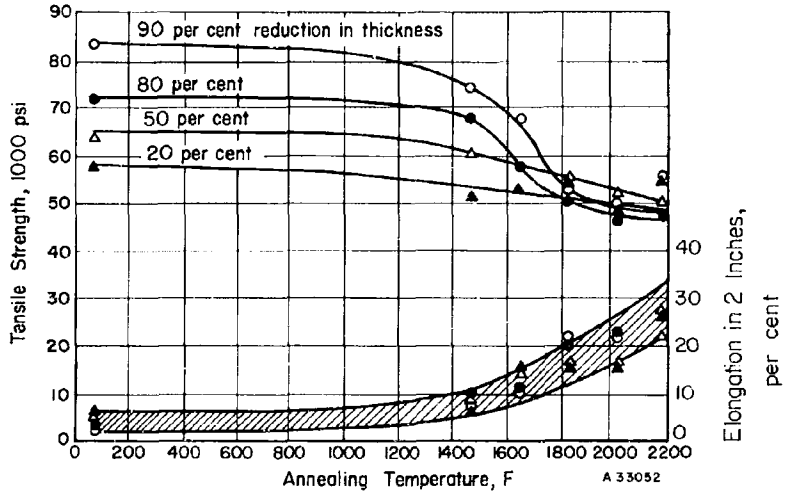


FIGURE A-8. ROOM-TEMPERATURE TENSILE PROPERTIES OF COMMERCIALLY PURE POWDER-METALLURGY COLUMBIUM AS A FUNCTION OF DEFORMATION AND ANNEALING TEMPERATURE[19]

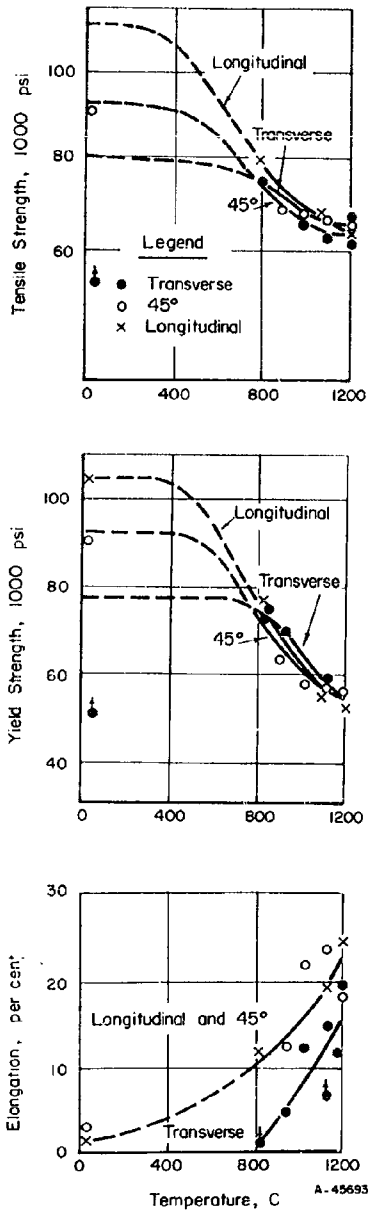


FIGURE A-9. TENSILE-PROPERTY DIRECTIONALITY OF COLUMBIUM SHEET (0.030 INCH)[20]

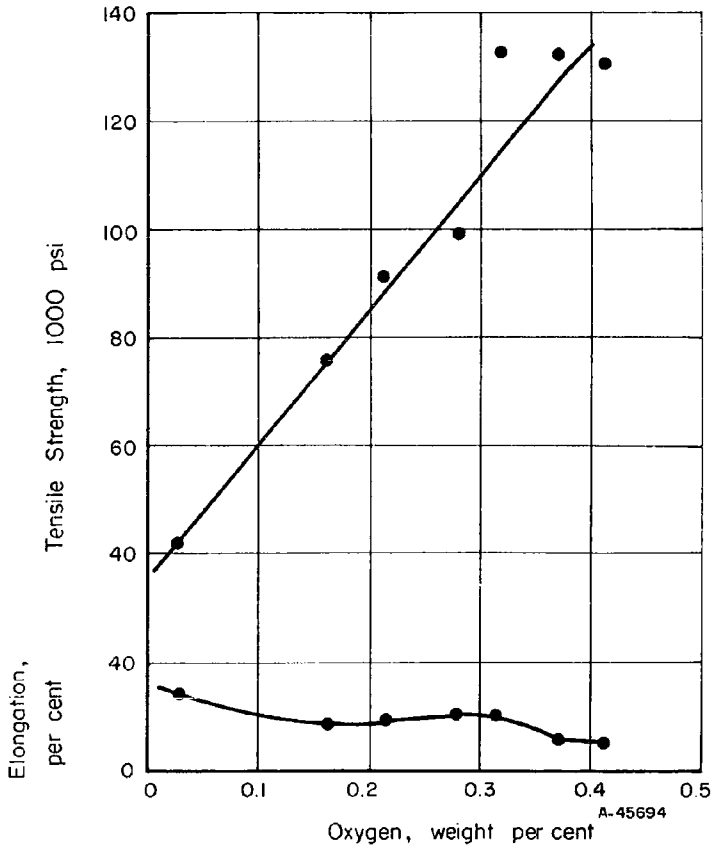


FIGURE A-10. EFFECT OF OXYGEN CONTENT ON THE ROOM-TEMPERATURE STRENGTH AND DUCTILITY OF COMMERCIAL-PURITY COLUMBIUM[11]

TABLE A-6. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF ANNEALED COLUMBIUM[21]

Temperature, C	Tensile Strength, tsi	Elongation in 1.25 Inch, per cent	Modulus of Elasticity, 10^6 psi
20	22.1	19.2	15.2
200	23.9	14.2	14.7
300	20.0	13.2	14.5
400	21.9	13.3	14.6
500	22.0	9.6	14.2
600	20.8	17.5	--
660	20.8	22.4	--
800	20.1	20.7	--
970	12.3	37.5	--
1050	7.2	42.5	--

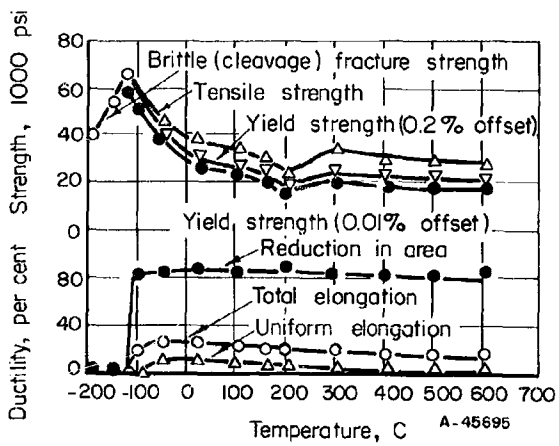


FIGURE A-11. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF COMMERCIALLY PURE ANNEALED (2 HOURS AT 2190 F) COLUMBIUM[22]

Test Rate: 360 per cent per hour
Analyses: 0.0114% C, 0.012% N, 0.021% O, <0.10% Zr, and 0.338% Ta
Hardness: 110 DPH
Grain Size: ASTM 1

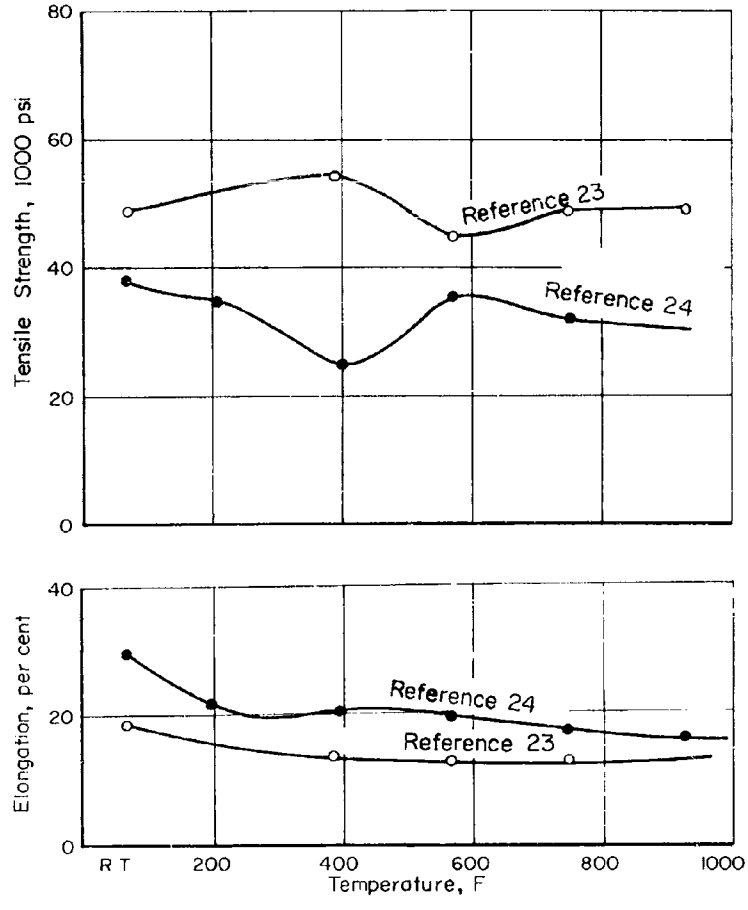


FIGURE A-12. TENSILE BEHAVIOR OF COLUMBIUM AT SLIGHTLY ELEVATED TEMPERATURES

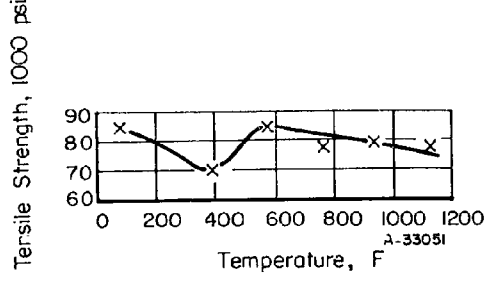


FIGURE A-13. EFFECT OF MODERATE TEMPERATURE ON THE STRENGTH OF COMMERCIALLY PURE COLD-ROLLED (70 PER CENT) COLUMBIUM[7]

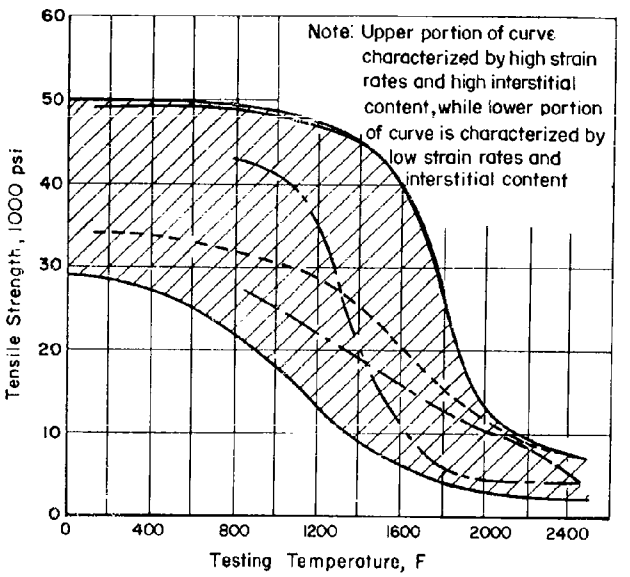


FIGURE A-14. EFFECT OF TEMPERATURE ON TENSILE STRENGTH OF COLUMBIUM[7]

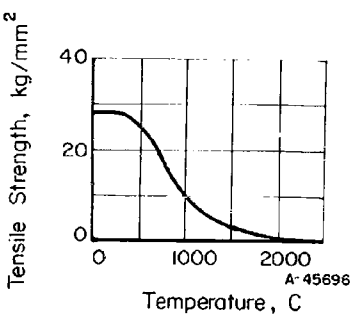


FIGURE A-15. EFFECT OF TEMPERATURE ON THE STRENGTH OF COLUMBIUM SHEET (0.012 INCH)[25]

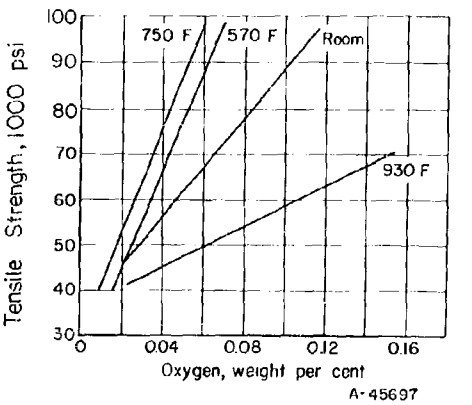


FIGURE A-16. EFFECT OF OXYGEN ON THE TENSILE STRENGTH OF COLUMBIUM AT VARIOUS TEMPERATURES[23]

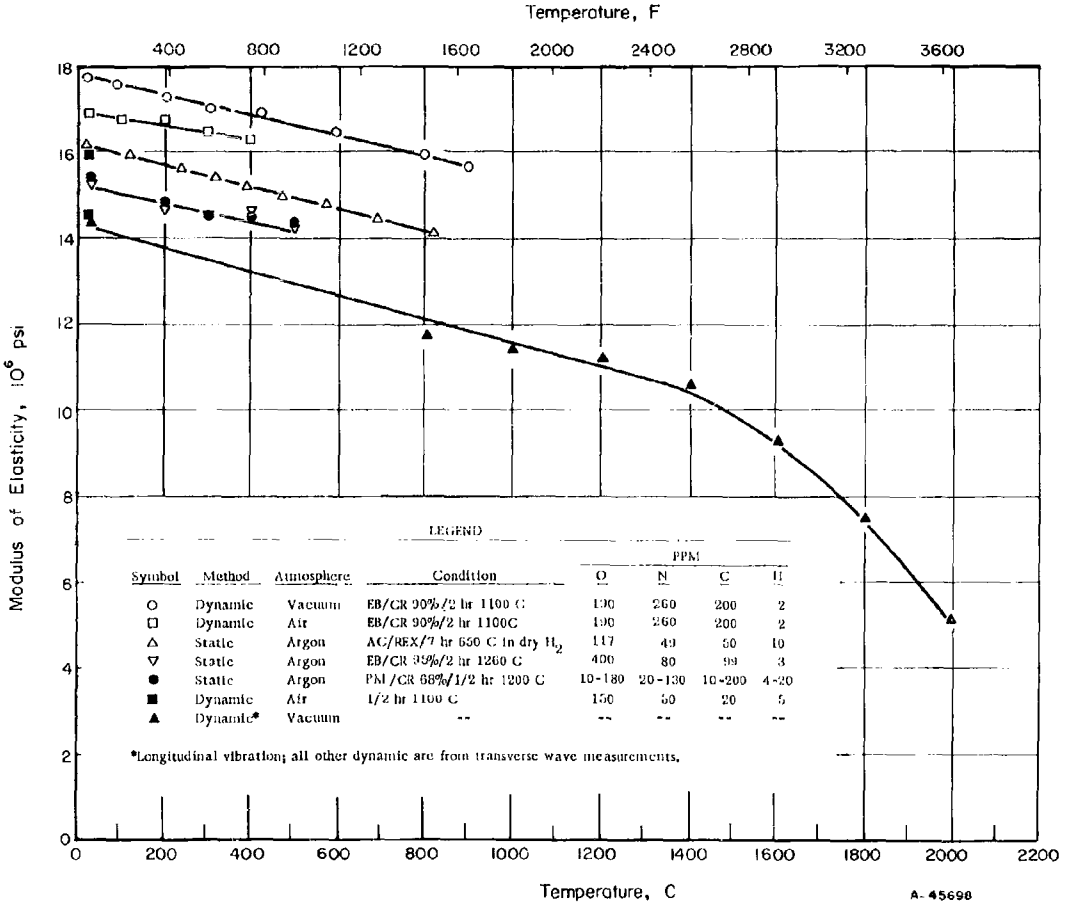


FIGURE A-17. MODULUS OF ELASTICITY OF COLUMBIUM AS A FUNCTION OF TEMPERATURE[12]

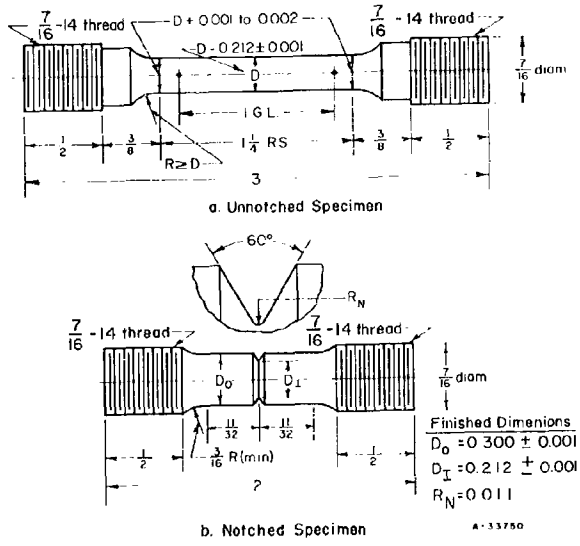


FIGURE A-18. UNNOTCHED AND NOTCHED BAR TENSILE TEST SPECIMENS USED TO OBTAIN DATA SHOWN IN FIGURES A-19 AND A-20

All dimensions are in inches.

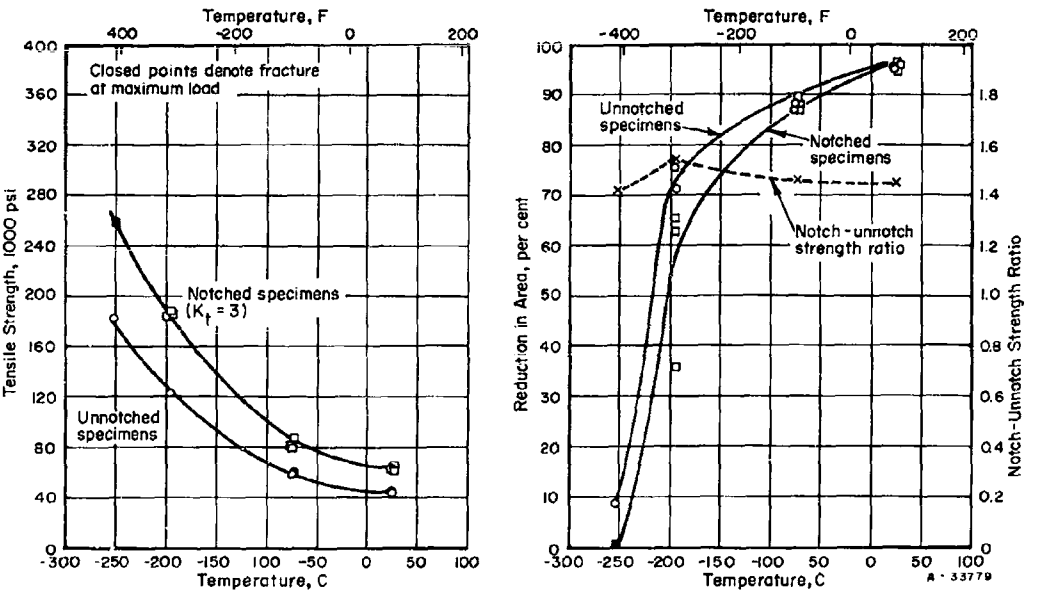


FIGURE A-19. TENSILE PROPERTIES FOR WROUGHT, STRESS-RELIEVED, ELECTRON-BEAM-MELTED COLUMBIUM BAR (1 HR AT 750 C; HARDNESS 100 VHN)[8]

	Unnotched	Notched
Crosshead Speed, in./min	0.02	0.005

Impurity	Weight Per Cent
C	0.004
O	0.015
N	0.005
Ta	0.180
Others	<0.10

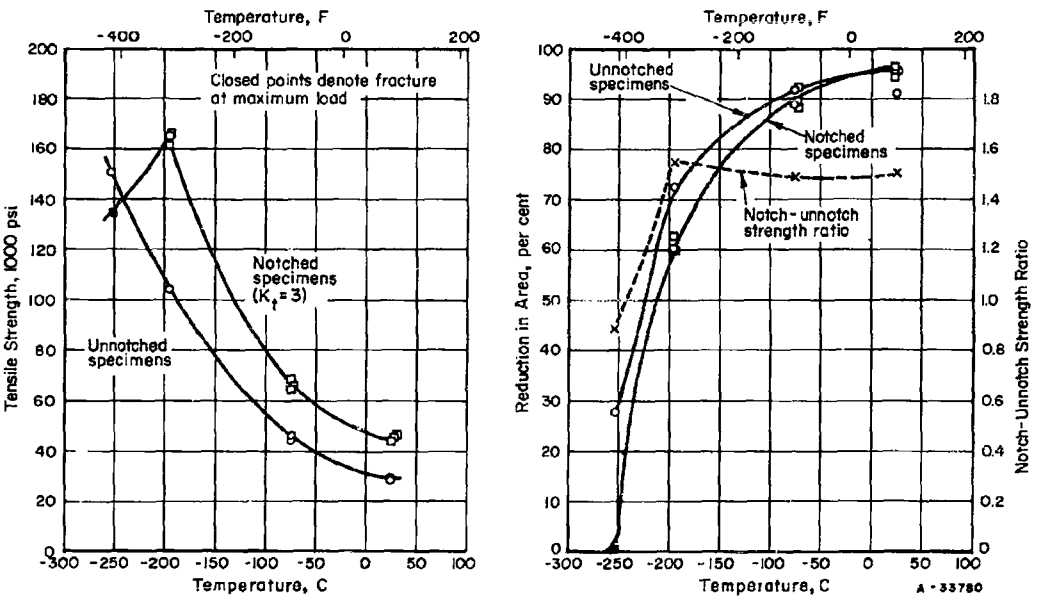
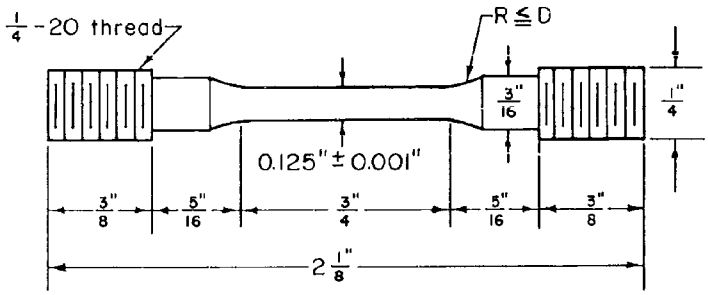


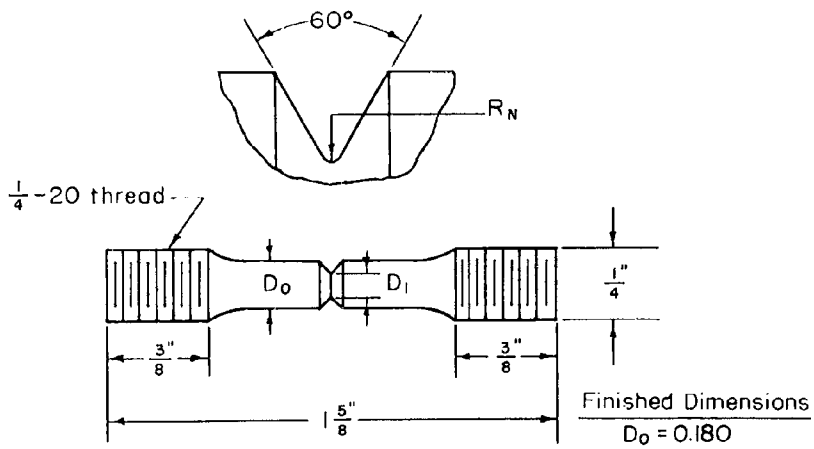
FIGURE A-20. TENSILE PROPERTIES FOR RECRYSTALLIZED, ELECTRON-BEAM-MELTED COLUMBIUM BAR (1/4 HR AT 1100 C; HARDNESS 64 VHN; ASTM 5, 9)[8]

	Unnotched	Notched
Crosshead Speed, in./min	0.02	0.005

Impurity	Weight Per Cent
C	0.004
O	0.015
N	0.005
Ta	0.180
Others	<0.10



a. Unnotched Tensile Test Specimen



Finished Dimensions

$D_O = 0.180$
$D_I = 0.125$
$R_N = 0.006$

b. Notched Tensile Test Specimen ($K_t = 30$)

A 38984

FIGURE A-21. UNNOTCHED AND NOTCHED-BAR TENSILE TEST SPECIMENS USED TO OBTAIN DATA SHOWN IN FIGURES A-22 THROUGH A-25

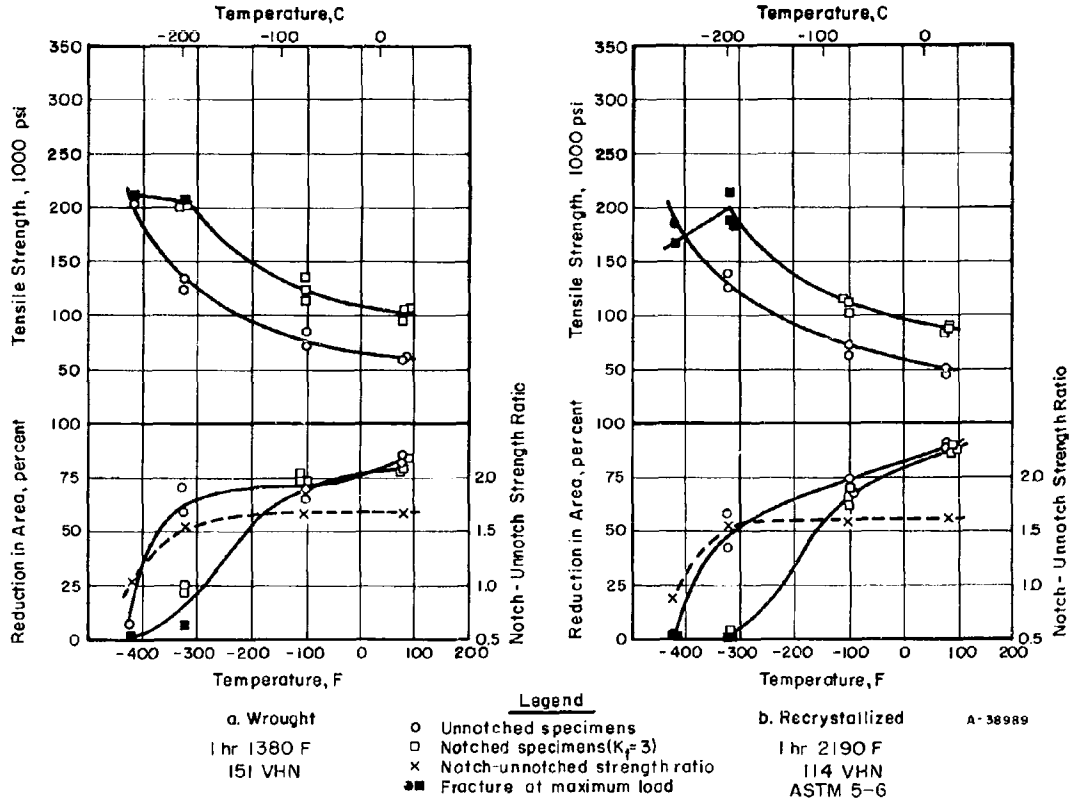


FIGURE A-22. TENSILE PROPERTIES FOR WROUGHT AND RECRYSTALLIZED, ELECTRON-BEAM-MELTED COLUMBIUM BAR CONTAINING 484 PPM OXYGEN AND 11 PPM HYDROGEN[9]

	Unnotched	Notched
Crosshead speed, in./min	0.02	0.005

Bar material 98 ppm combined carbon and nitrogen.

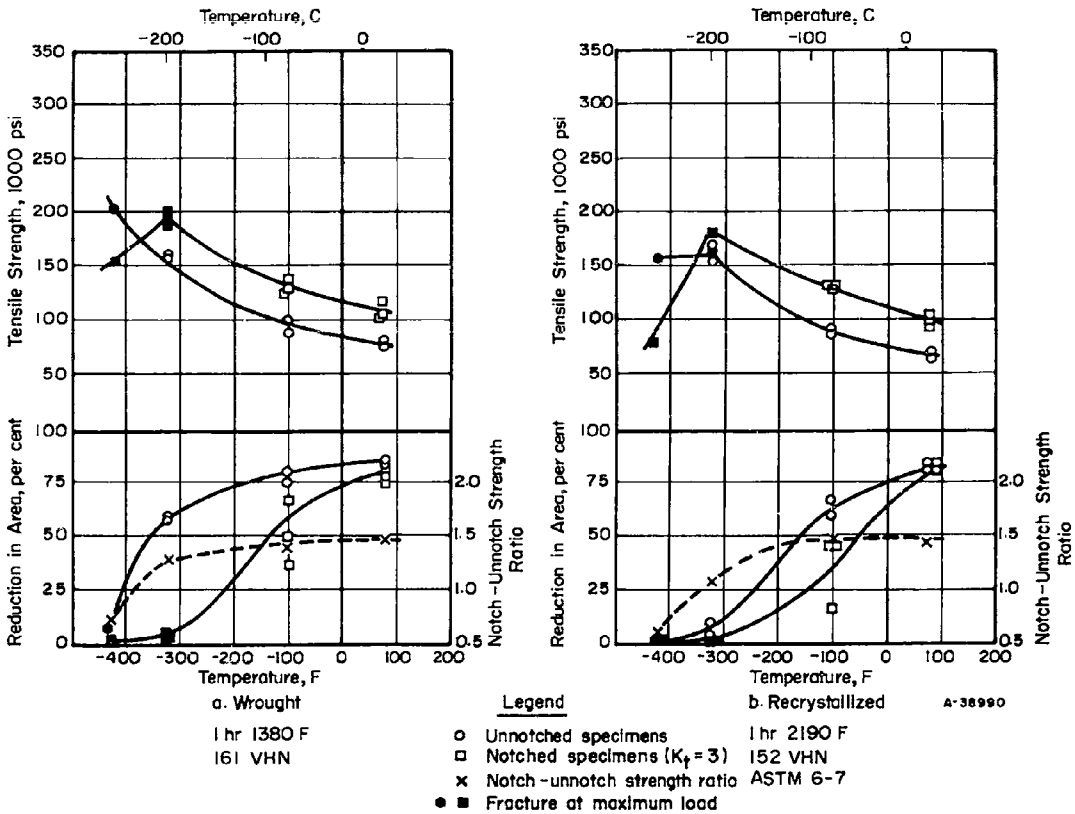


FIGURE A-23. TENSILE PROPERTIES FOR WROUGHT AND RECRYSTALLIZED, ELECTRON-BEAM-MELTED COLUMBIUM BAR CONTAINING 1320 PPM OXYGEN AND 21 PPM HYDROGEN[9]

	Unnotched	Notched
Crosshead Speed, inch per minute	0.02	0.005

Bar material 98 ppm combined carbon and nitrogen.

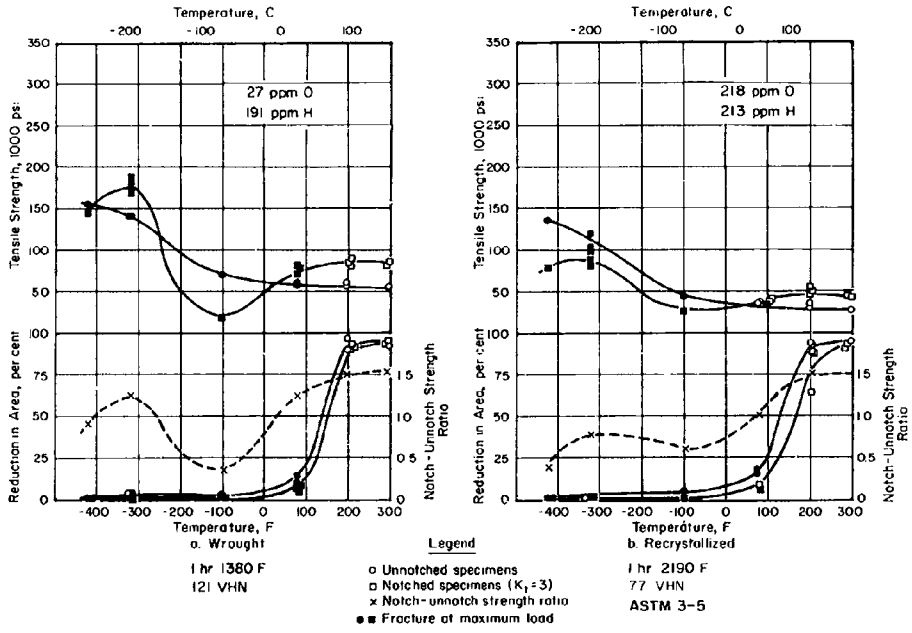


FIGURE A-24. TENSILE PROPERTIES FOR WROUGHT AND RECRYSTALLIZED, ELECTRON-BEAM-MELTED COLUMBIUM BAR CONTAINING "LOW" HYDROGEN[9]

	Unnotched	Notched
Crosshead Speed, inch per minute	0.02	0.005

Bar material 98 ppm combined carbon and nitrogen.

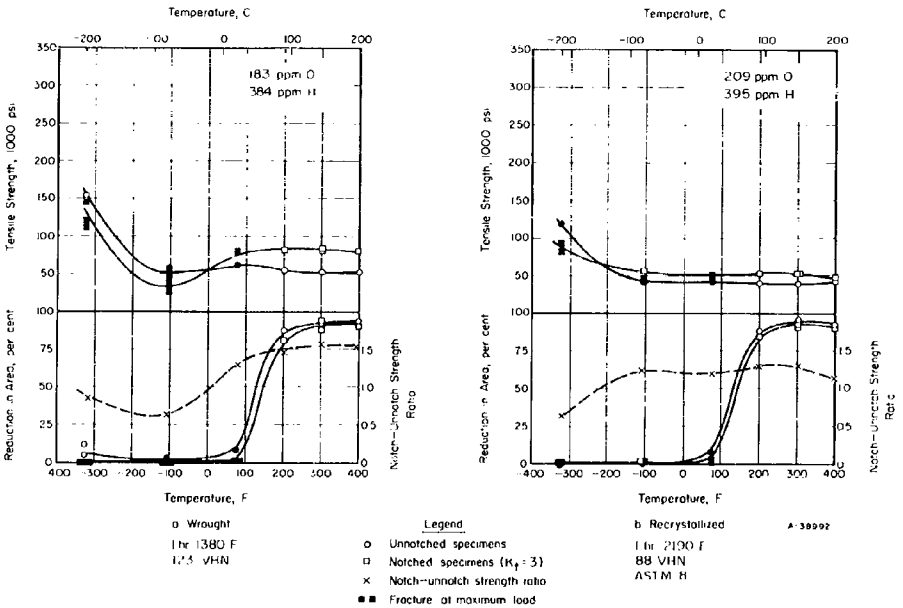


FIGURE A-25. TENSILE PROPERTIES FOR WROUGHT AND RECRYSTALLIZED, ELECTRON-BEAM-MELTED COLUMBIUM BAR CONTAINING "HIGH" HYDROGEN[9]

	Unnotched	Notched
Crosshead Speed, inch per minute	0.02	0.005

Bar material 98 ppm combined carbon and nitrogen.

TABLE A-7. CREEP PROPERTIES OF COLUMBIUM [a][18]

Condition	Temp, C	Stress, tsi	Time Required for Specified Creep Strain, hours 0.05%	0.1%	0.2%	0.3%	0.5%	1.0%	Minimum Creep Rate, in./in./hr x 10^{-6}	Duration of Test, hours	Total Creep Strain, per cent
Annealed 1100 C	400	4	160	800	--	--	--	--	0.44	1819	0.145
Annealed 1100 C		6	115	445	2020	--	--	--	0.58	2700	0.224
Annealed 1100 C		8	20	120	645	--	--	--	0.86	1603	0.286
Annealed 1150 C		8	22	152	608	--	--		0.87	1536	0.289
Annealed 1100 C	500	4	--	--	--	--	--	--	0.52	362	0.037
Annealed 1150 C		8	90	195	--	--	--	--	0.53	725	0.171
Annealed 1150 C		8	85	140	390	--	--	--	0.24	1870	0.270
Annealed 1150 C		10	22	59	123	--	--	--	5.3	338	0.345
As rolled		10	--	10	18	35	400	1295 (0.6%)	--	--	--
Annealed 1100 C	600	4	27	110	1470	--	--	--	1.6	1325	0.34
Swaged bar		4	50	160	860	2130	--	--	--	5519	0.306
Annealed 1300 C		5	5	15	35	--	165	980	2.3	1359	1.68
As rolled		6	40	130	345	1160	--	--	--	--	--
Annealed 1100 C		8	15	60	--	--	--	--	0.2	2117	0.198
Swaged bar	700	1	40	290	1560	--	--	-	--	2314	0.22
Swaged bar		2	80	205	550	1495	--	--	--	5008	0.36
Swaged bar		3	120	220	540	1115	--	--	--	3335	0.40
Swaged bar	1000	2.8	--	--	--	--	--	24	--	--	--
Swaged bar		5.0	24	--	--	--	--	--	--	--	--

(a) 99.92+% Cb.

TABLE A-8. CREEP AND CREEP-RUPTURE BEHAVIOR FOR WROUGHT COLUMBIUM[10]

Temperature, F	Stress for Rupture in 1 hr, psi	10 Hr-Stress for 0.05% Creep	0.1% Creep	0.2% Creep	Rupture	100-Hr Stress for 0.05% Creep	0.1% Creep	0.2% Creep	Rupture	1000-Hr Stress for 0.05% Creep	0.1% Creep	0.2% Creep
750	--	23,000	40,000	52,000	--	12,000	20,000	29,000	--	6,500	9,500	15,500
930	--	27,000	31,000	33,500	--	17,500	20,000	23,000	--	11,500	13,500	16,000
1290	--	--	--	--	--	--	2,900	3,600	--	--	2,400	1,700
1600	9000	--	--	--	7900	--	--	--	6900	--	--	--
1800	7000	--	--	--	6500	--	--	--	6100	--	--	--
2190	5200	--	--	--	4600	--	--	--	4000	--	--	--

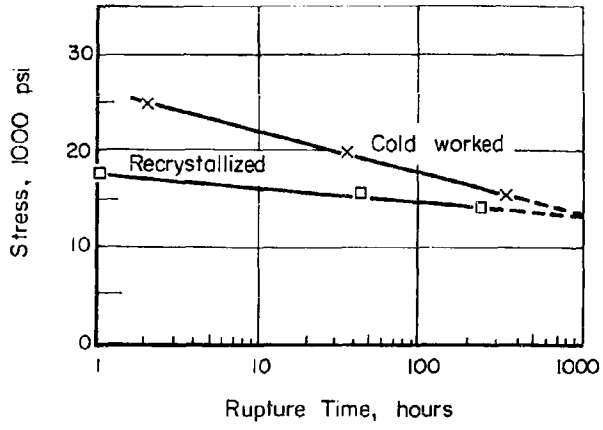


FIGURE A-26. STRESS-RUPTURE CHARACTERISTICS OF COLD-WORKED AND RECRYSTALLIZED COLUMBIUM AT 1800 F[26]

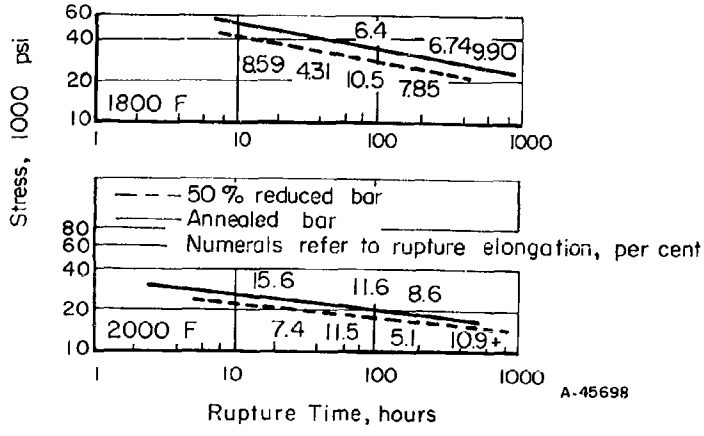


FIGURE A-27. STRESS-RUPTURE CHARACTERISTICS OF WROUGHT AND ANNEALED COMMERCIAL PURITY COLUMBIUM AT 1800 AND 2000 F[27]

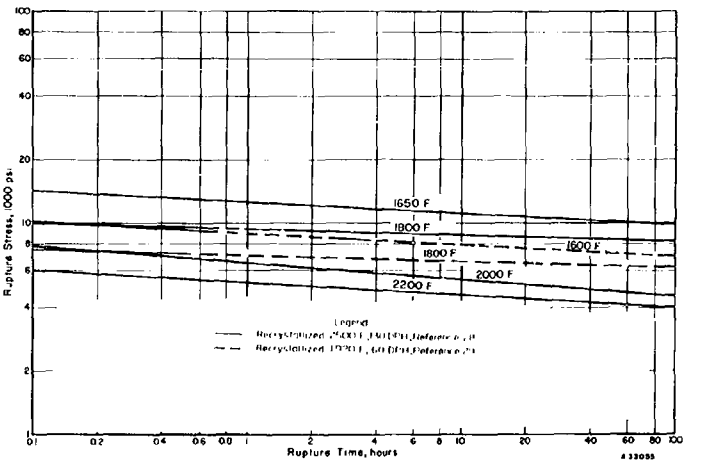


FIGURE A-28. RUPTURE CURVES FOR COMMERCIALLY PURE RECRYSTALLIZED COLUMBIUM

TABLE A-9. HARDNESS VARIATION WITH COLD REDUCTION FOR COMMERCIAL POWDER-METALLURGY COLUMBIUM[21]

Reduction in Area, per cent	Hardness, VHN	
	Perpendicular to Rolling Direction	Parallel to Rolling Direction
0	84	84
10	104	104
20	119	114
30	129	119
40	137	123
50	143	128
60	148	133

TABLE A-10. HARDNESS VARIATION WITH COLD REDUCTION FOR COLUMBIUM[5]

Reduction by Cold Rolling, per cent	Hardness, VHN	
	Powder Metallurgy	Electron-Beam Melted
0	95	54
20	144	91
40	151	112
60	164	130
80	167	145
90	179	154

TABLE A-11. HOT HARDNESS OF COMMERCIAL POWDER-METALLURGY COLUMBIUM[39]

Temperature, C	20	400	600	800	1000	1200
Hardness, kg/mm^2	89	82	73	37	29	21

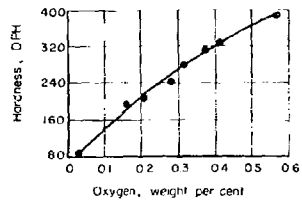


FIGURE A-29. EFFECT OF OXYGEN CONTENT ON THE HARDNESS OF COMMERCIAL-PURITY COLUMBIUM[11]

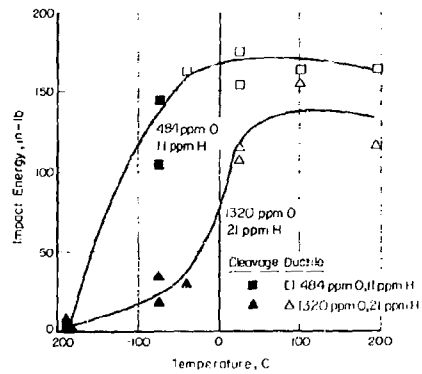


FIGURE A-30. EFFECT OF OXYGEN CONTENT ON THE IMPACT PROPERTIES OF WROUGHT ELECTRON-BEAM-MELTED COLUMBIUM[31]

Starting material contained 98 ppm combined carbon and nitrogen.

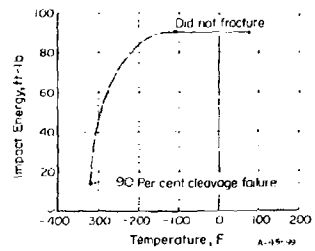


FIGURE A-31. IMPACT PROPERTIES OF ANNEALED POWDER-METALLURGY COLUMBIUM CONTAINING 140 PPM OXYGEN[29]

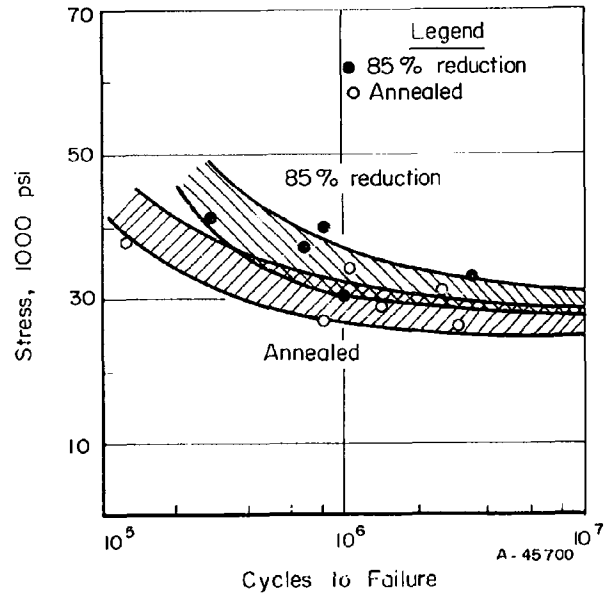


FIGURE A-32. FATIGUE CHARACTERISTICS OF COLD-WORKED AND ANNEALED POWDER-METALLURGY COLUMBIUM[15]

4. Metallurgical Properties

a. Fabricability: possesses excellent room temperature fabrication characteristics which are amenable to all conventional fabrication practices and can be fabricated to large reductions (>95 per cent) without the need for process annealing[30]

b. Transition temperature: <-320 F[8, 10]

c. Weldability: processes capable of excluding interstitial contaminants from the hot zone are readily adaptable to welding columbium[10]; weld properties are essentially the same as those of the base metal[6]

d. Stress-relief temperature: 1 hour 1380 F[8]
1 hour 1600 F[2-4]
10 to 15 minutes at 1700 to 1800 F[6]

e. Recrystallization temperature: 1 hour at 2100 F[6]
1 hour at 2200 F[16]

Figures A-33 and A-34

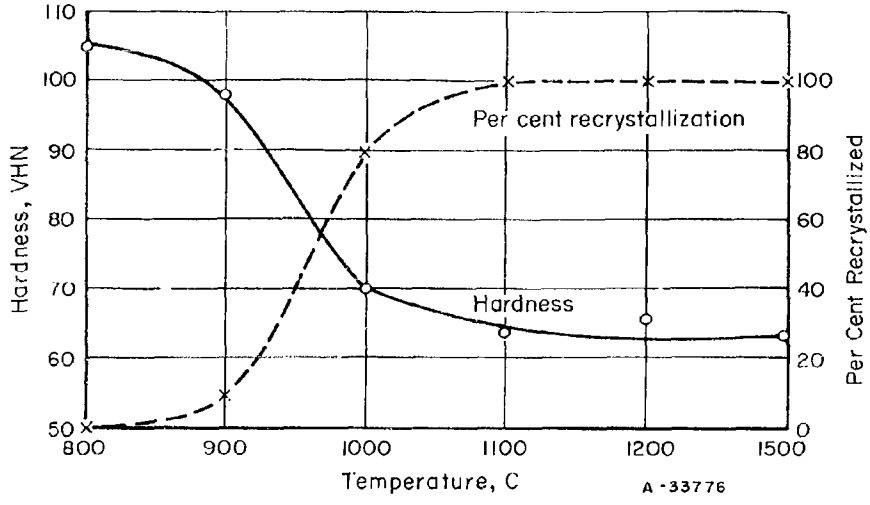


FIGURE A-33. ANNEALING CURVE FOR ELECTRON-BEAM-MELTED COLUMBIUM BAR[8]

1/4 hour at temperature, furnace cooled.

Electron-beam-melted ingot press forged and swaged at 1110 F followed by swaging at room temperature. Total reduction 89 per cent.

Impurity	Weight Per Cent
C	0.004
O	0.015
N	0.005
Ta	0.180
Others	<0.10

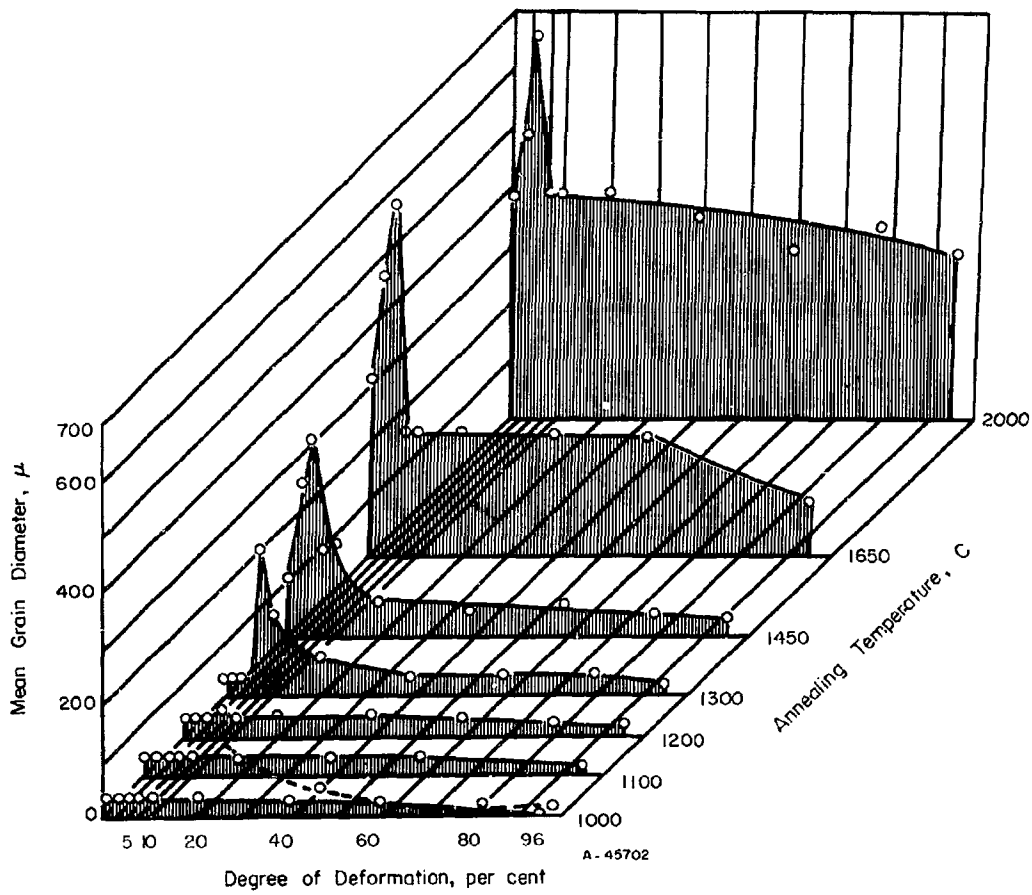


FIGURE A-34. ANNEALING TEMPERATURE VERSUS DEFORMATION AND GRAIN SIZE[32]

References

(1) Proposed ASTM Specification for Columbium and Columbium Alloy Ingots, Sixth Draft, American Society for Testing and Materials (March 13, 1962).

(2) Proposed ASTM Specifications for Columbium and Columbium Alloy Strip, Sheet, Foil and Plate, Sixth Draft, American Society for Testing and Materials (March 13, 1962).

(3) Proposed ASTM Specification for Columbium and Columbium Alloy Bar, Rod and Wire, Sixth Draft, American Society in Testing and Materials (March 13, 1962).

(4) Proposed ASTM Specification in Columbium and Columbium Alloy Seamless and Welded Tubes, Sixth Draft, American Society for Testing and Materials (March 13, 1962).

(5) Klopp, W. D., and Hodge, W., "Fabrication of Pure Columbium", Battelle Memorial Institute, DMIC Memorandum 34 (September 11, 1959).

(6) "SCb-100 (Pure Columbium)", Stauffer Metals Division Data Sheet.

(7) Bartlett, E. S., and Houck, J. A., "Physical and Mechanical Properties of Columbium and Columbium-Base Alloys", Battelle Memorial Institute, DMIC Report 125 (February 22, 1960).

(8) Imgram, A. G., et al., "Notch Sensitivity of Refractory Metals", Battelle Memorial Institute, WADD TR 60-278 (April 1960).

(9) Imgram, A. G., et al., "Notch Sensitivity of Refractory Metals", Battelle Memorial Institute, ASD TR 61-474 (August 1961).

(10) Metals Handbook, Properties and Selection of Metals, 8th Edition, American Society for Metals, Cleveland, Ohio (1961), Vol 1, pp 1202-1203.

(11) Tottle, C. R., "The Physical and Mechanical Properties of Niobium", J. Inst. Metals, 85, 377 (April, 1957).

(12) Tietz, T. E., and Wilson, J. W., "Mechanical, Oxidation, and Thermal Property Data for Seven Refractory Metals and Their Alloys", Lockheed Missiles and Space Division, Contract No as 60-6119-C, Code 2·36·61-1 (September, 1961).

(13) Rosenberg, H. M., "The Thermal Conductivity of Metals at Low Temperature", Phil. Trans., A247, 441 (1954-55).

(14) Fieldhouse, I. B., Hedge, J. C., and Lang, J. I., "Measurements of Thermal Properties", WADC TR 58-274 (November, 1958).

(15) Begley, R. T., "Development of Niobium Base Alloys", U. S. Atomic Energy Commission Report No. AZ388(WEC) (1957).

(16) "Haynes Columbium", New Product Data, Haynes Stellite Co.

(17) "General Properties of Columbium", Universal Cyclops Steel Corp., Technical Bulletin No. 1. 0. 1.

(18) Tottle, C. R., "Niobium and Its Alloys", Nucl. Eng., 3 (1958).

(19) Page, J. P., "The Annealing Behavior of Cold-Rolled Niobium", ORNL2372 (September, 1957).

(20) Anders, F. J., and Pollock, W. L., "Tensile Properties and Rolling Textures of Niobium Sheet", The Technology of Columbium (Niobium), Johy Wiley, New York (1958).

(21) Heal, T. J., "The Mechanical and Physical Properties of Magnesium and Niobium Canning Materials", Second U. N. International Conference on the Peaseful Uses of Atomic Energy, Geneva (1958).

(22) Wessel, E. T., and Lathers, D. D., "The Ductile-to-Brittle Transition in Niobium", The Technology of Columbium (Niobium), John Wiley, New York (1958).

(23) Vaughan, H. G., and Rose, R. G., "The Tensile Properties of Columbium", Kingdom Atomic Energy Authority, IGR-TN (C-583) (November, 1958).

(24) Begley, R. T., "Development of Niobium-Base Alloys", Westinghouse Electric Corp., WADC TR 57-344 (November, 1957).

(25) Mordike, B. L., and Fitzgerald, L. M., "Some Preliminary Observations on Methods of Measuring Mechanical Properties of Solids at High Temperature", Oxford University, Dept. of Metallurgy, Conference on the Study of Metals and Alloys Above 1200°C, Oxford (September, 1958).

(26) Brown, C. M., and Fountain, R. W., "New Metals Face The Future", J. Metals, 10, 330 (1958).

(27) "Columbium-Base Alloys for High Temperature Use", Material Design Engineering, 47, 144 (1958).

(28) Gemmel, G. D., "Some Effects of Alloying on the Strength Properties of Columbium at Elevated Temperatures", paper from Symposium on Metallurgy of Columbium and Its Alloys, National Metal Exposition (October, 1958).

(29) Begley, R. T., "Development of Niobium-Base Alloys", Westinghouse Electric Corp., WADC TR 57-344 (Part II) (December, 1958).

(30) Miller, G. L., Tantalum and Niobium, Academic Press Inc. (1959).

(31) Imgram, A. G., unpublished data obtained at Battelle Memorial Institute (1963).

(32) Savitskii, E. M., Barov, V. V., and Ivanova, K. N., "The Recrystallization Diagram of Columbium Doklady Akad. Nauk SSSR, 126 (4), 771-73 (June, 1959); translated in Amer. Inst. Phys. "Soviet Physics", Doklady, 4 (3), 670 (December, 1959).

Cb-1Zr

1. Identification of Material

   a. Designation: many, depending upon individual supplier

   b. Chemical Composition: Tables A-12 through A-14

   c. Forms available: ingot, strip, sheet, foil, plate, bar, rod, wire, and tube[1-4]

TABLE A-12. CHEMICAL REQUIREMENTS FOR REACTOR-GRADE Cb-1Zr PRODUCED BY FUSION, POWDER METALLURGY, OR OTHER SUITABLE MEANS TO PRODUCE CONSOLIDATED METAL FOR PROCESSING TO VARIOUS BASIC SHAPES[a][1-4]

Element		Content, Maximum, ppm
C	Each ingot	100
N		300
O		300
H		20
Zr		0.8-1.2% (range)
Fe		500
Ta		1000
Ti		500
Si		300
B		2
W	When so specified	500
Mo		1000
Cd		5
Co		30
Pb		50
Mn		100
Ni		200
V		200
Hf		100
Cb, by difference		98.5% min

(a) For ingot, strip, sheet, foil, plate, bar, rod, wire, and tube.

TABLE A-13. CHEMICAL REQUIREMENTS FOR Cb-1Zr STARTING INGOT AND FABRICATED SHAPES AS SUPPLIED BY WAH CHANG[5]

Element		Content, Maximum, ppm
Cb	Starting ingot and fabricated shapes	98.5% min
Zr		0.8-1.2% (range)
C		100
N		300
O		300
H		20
B	Starting ingot	1
Cd		5
Co		30
Hf		100
Fe		500
Pb		50
Mn		100
Mo		1000
Ni		200
Si		300
Ta		1000
Ti		500
W		200
V		200
Total rare earths		100

TABLE A-14. CHEMICAL REQUIREMENTS FOR Cb-1Zr FABRICATED SHAPES AS SUPPLIED BY DU PONT[6]

Element	Content, Maximum, weight per cent	
	(a)	(b)
Zr	0.75 min - 1.25 max	0.75 min - 1.25 max
O	0.0200	0.0200
H	0.0020	0.0020
N	0.0100	0.0100
C	0.0100	0.0050
Cb	By difference	By difference

(a) Sheet and strip.

(b) Plate, rectangular bar, round bar, and tube hollows.

2. Physical Properties

a. Melting point: 4350 F[7,8]; 4375 F[5]

b. Density: 0.31 lb/in.^{3}[7,8]

3. Mechanical Properties

a. Tensile Properties at Room Temperature

Ultimate tensile strength: Tables A-15 through A-18

Tensile yield strength: Tables A-15 through A-18

Elongation: Tables A-15 through A-18

Reduction in area: Table A-16

Modulus of elasticity: 15×10^6 psi[8]; 16×10^6 psi[7]

b. Effect of Temperature on Tensile Properties

Ultimate tensile strength: Table A-19

Tensile yield strength: Table A-19

Elongation: Table A-19

Modulus of elasticity: average of two tests on recrystallized material[5]

Temperature, F	Modulus of Elasticity, 10^6 psi
75	11.5
2500	2.7
2700	2.0
3000	0.8

c. Creep and Stress-Rupture Properties

Table A-20
Figure A-35

d. Other Selected Mechanical Properties

Shear strength: data at room temperature and 1600 F have been determined for fastener material[10]

Type Fastener	Diameter, inch	Shear Strength, 1000 psi RT	Shear Strength, 1000 psi 1600 F
Huck rivet	0.125	38.5	32.0
		43.5	32.0
Deutsch rivet	0.125	35.0	26.0
		33.0	--
Du Pont explosive	0.125	27.0	13.0
		26.0	13.0

Bend ductility: for sheet material bent over a 2T bend radius, 180 degrees, at a ram speed of 13 inches per minute[5]

Condition	Bend Results[a] 75 F	Bend Results[a] -100 F
As rolled	NF, NF, NF	F, NF, NF
Stress relieved 1 hr 1650 F	PF, NF, NF	PF, NF, NF
Recrystallized 1 hr 2200 F	NF, NF, NF	NF, NF, NF

(a) NF = no fracture
PF = partial fracture
F = fracture.

Impact: Table A-21

TABLE A-15. TENSILE-PROPERTY REQUIREMENTS FOR REACTOR GRADE Cb-1Zr PRODUCTS[a][2-4]

Maximum Tensile Strength, 1000 psi	Maximum Yield Strength (0.2% Offset), 1000 psi	Minimum Elongation in 1 Inch[b], per cent
75	60	10

(a) For strip, sheet, foil, plate, bar, rod, wire, and tube. Properties for stress-relieved material (1600 F minimum) tested at 0.002 to 0.005 inch per inch per minute through 0.6 per cent offset, and 0.02 to 0.05 inch per inch per minute to fracture.
(b) Elongation for tube products to be in 2 inches.

TABLE A-16. ROOM-TEMPERATURE TENSILE PROPERTIES FOR Cb-1Zr FABRICATED SHAPES IN THE RECRYSTALLIZED CONDITION[a][6]

Comments	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent
		Sheet and Strip[b]		
0.006 in. to 0.020 in., min. values	35	20	12 (2 in.)	--
Over 0.020 in. to 0.187 in., incl., min. values	35	20	15 (2 in.)	--
		Plate and Rectangular Bar[c]		
Typical average	30	15	25 (2 in. or 4D)	--
Probable minimum	25	12	15 (2 in. or 4D)	--
		Round Bar[c]		
Typical average	35	20	45 (4D)	85
Probable minimum	30	16	25 (4D)	50

(a) Test rate 0.005 ± 0.002 inch per inch per minute through 0.6 per cent offset, then 0.05 ± 0.02 inch per inch per minute to failure.
(b) Typical analyses 0.75 min - 1.25 max % Zr, 0.0200% O, 0.0020% H, 0.0100% N, and 0.0100% C.
(c) Typical analyses 0.75 min - 1.25 max % Zr, 0.0200% O, 0.0020% H, 0.0100% N, and 0.0050% C.

TABLE A-17. SOME SELECTED ROOM-TEMPERATURE TENSILE PROPERTIES OF Cb-1Zr SHEET

Condition	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent	Reference
Annealed sheet (1 hr 2200 F, 0.040-inch)[a]	50	40	12	(8)
Annealed sheet[b]	45	30	25	(7)
Recrystallized sheet[c]	48.1	35.4	15	(5)

(a) Typical analyses 1% Zr, 0.0100% C, 0.0250% O, <0.0100% N, and 0.0015% H.
(b) Electron-beam melted. Typical analyses 98.9% Cb, 0.5-1.0% Zr, 0.0050% C, 0.0150% O, 0.0100% N, 0.0005% H, 0.0500% Ta, and 0.0150% others.
(c) Typical analyses 98.5% min Cb, 0.8-1.2% Zr, <0.0100% C, <0.0300% N, <0.0300% O, and <0.0020% H.

TABLE A-18. ROOM-TEMPERATURE TENSILE PROPERTIES OF Cb-1Zr TUBING[a](5)

Condition	Size, inch	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 1 Inch, per cent
Stress relieved 1 hr 1800 F	1.103 OD x 0.052 wall	55.4	40.8	25.5
		56.1	42.1	22.5
Recrystallized 1 hr 2200 F	1.5 OD x 0.066 wall	35.8	26.9	30.5
		35.8	23.0	33.0
		40.7	24.7	44.0
		40.6	23.7	40.5
	0.253 OD x 0.066 wall	38.1	23.0	41.5
		38.4	23.6	41.5
	0.676 OD x 0.121 wall	39.3	21.1	59.0
		40.0	22.4	62.5

(a) Typical analyses 98.5% min Cb, 0.8-1.2% Zr, <0.0100% C, <0.0300% N, <0.0300% O, and <0.0020% H.

TABLE A-19. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF RECRYSTALLIZED Cb-1Zr[a](5)

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1 inch, per cent
75	48.0	37.1	15
	47.5	33.7	15
2000	22.9	21.4	12
	22.8	20.0	15
2500	8.65	7.0	>50
	8.15	6.24	>46
2700	5.9	4.6	>47
	6.16	5.0	>40
3000	2.95	2.34	>48
	3.47	2.94	>35

(a) Typical analyses 98.5% min Cb, 0.8-1.2% Zr, <0.0100% C, <0.0300% N, <0.0300% O, and <0.0020% H.

TABLE A-20. CREEP AND STRESS-RUPTURE DATA FOR WORKED AND ANNEALED Cb-1Zr TESTED IN ARGON[5]

Cold Work, per cent	Condition	Temperature, F	Stress, 1000 psi	Primary Creep Strain, per cent	Minimum Creep Rate, in./in./hr	Rupture Time, hours	Elongation, per cent	Reduction in Area, per cent
20	As worked	1800	15.0	2.0	2.0×10^{-3}	52	26	61
40	As worked		17.5	1.0	1.2×10^{-2}	10	21	77
60	As worked		17.5	7.5	4.8×10^{-3}	24	18	60
20	As worked	1800	12.5	1.9	3.0×10^{-6}	1001[a]	0.6	0.6
40	As worked		12.5	1.4	4.0×10^{-6}	1018[a]	0.6	1.5
60	As worked		12.5	1.6	1.7×10^{-5}	1000[a]	1.2	1.5
80	As worked		12.5	3.9	2.4×10^{-5}	1032[a]	1.6	1.5
20	As worked	2000	10.0	1.5	1.4×10^{-3}	143	42	67
40	As worked		10.0	2.0	5.8×10^{-3}	33	42	74
60	As worked		10.0	9.0	8.6×10^{-3}	27	47	77
80	As worked		10.0	3.0	7.0×10^{-3}	30	40	71
20	Annealed[b]	1600	25.0	0.6	2.5×10^{-4}	57	7	53
40	Annealed		25.0	0.9	8.0×10^{-4}	28	6	55
95	Annealed		25.0	5.0	1.0×10^{-3}	49	19	71
20	Annealed	1800	15.0	2.5	8.0×10^{-4}	216	19	75
40	Annealed		15.0	0.5	1.5×10^{-3}	70	31	62
60	Annealed		15.0	2.0	2.7×10^{-4}	185	15	65
80	Annealed		15.0	--	1.1×10^{-2}	14	28	77
95	Annealed		15.0	0.5	2.2×10^{-3}	20	13	66
20	Annealed	1800	12.5	1.3	3.5×10^{-6}	1004[a]	0.6	1.3
40	Annealed		12.5	0.7	5.3×10^{-6}	1015[a]	0.7	1.5
60	Annealed		12.5	1.0	2.1×10^{-5}	1196[a]	1.6	1.8
80	Annealed		12.5	2.4	1.1×10^{-5}	1004[a]	1.9	3.7
20	Annealed	2000	10.0	0.9	1.3×10^{-3}	130	24	70
40	Annealed		10.0	2.5	2.9×10^{-4}	37	45	75
60	Annealed		10.0	1.0	1.6×10^{-3}	63	17	73
95	Annealed		10.0	1.0	1.3×10^{-4}	74	30	73

(a) Discontinued prior to failure.
(b) 1 hour at 2190 F.

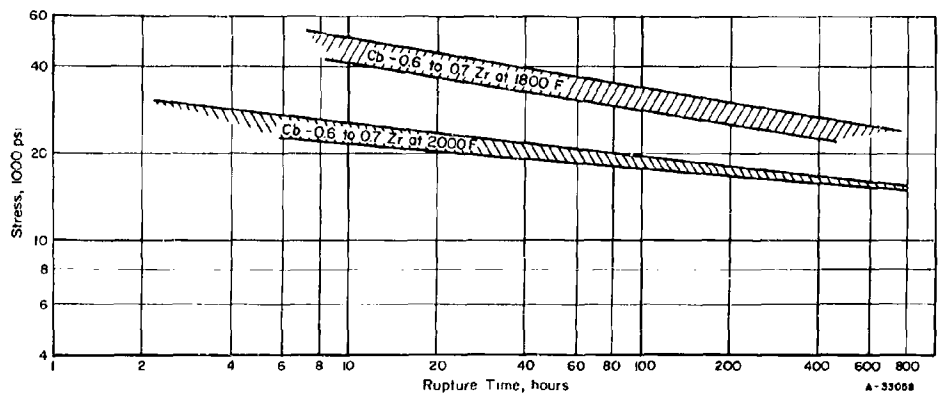


FIGURE A-35. STRESS-RUPTURE PROPERTIES OF Cb-1Zr AT 1800 AND 2000 F[9]

TABLE A-21. CHARPY IMPACT DATA FOR Cb-1Zr[a][5]

Condition	Temperature, F	Rupture Strength[b], ft-lb
	Unnotched	
As rolled	75	156 NF
	-100	133 PF
Stress relieved 1 hr 1650 F	75	129 NF
	-100	126 NF
Recrystallized 1 hr 2200 F	75	128 NF
	-100	121 NF
	Notched	
As rolled	75	>60 PF[c]
	-100	69 PF
Stress relieved 1 hr 1650 F	75	119 PF
	-100	95 PF
Recrystallized 1 hr 2200 F	75	93 PF
	-100	116 NF

(a) Typical analyses 98.5% min Cb, 0.8-1.2% Zr, <0.0100% C, <0.0300% N, <0.0300% O, and <0.0020% H.

(b) NF = no fracture
PF = partial fracture.

(c) Specimen stopped hammer, 60 ft-lb range.

4. Metallurgical Properties

a. Fabricability: ingots are forged at 1200 to 1800 F to at least 50 per cent reduction to develop optimum properties; conditioned and annealed sheet bars are generally rolled at breakdown temperatures of 400 to 600 F; final rolling up to 80 per cent is possible at room temperature[7]

b. Weldability: both electron-beam and inert-gas fusion welding can be satisfactorily used; high-purity atmospheres are mandatory to prevent embrittlement of the material[7]; weld ductility is about the same as that of the base metal[5]

c. Stress-relief temperature: 1 hour at 1650 to 1800 F[5]; 1 hour at 2100 F[7]

d. Recrystallization temperature: 1 hour at 2200 F[5, 8]; 1 hour at 2250 F[7]

References

(1) Proposed ASTM Specifications for Columbium and Columbium Alloy Ingots, Sixth Draft, American Society for Testing and Materials (March 13, 1962).

(2) Proposed ASTM Specifications For Columbium and Columbium Alloy Strip, Sheet, Foil, and Plate, Sixth Draft, American Society For Testing and Materials (March 13, 1962).

(3) Proposed ASTM Specifications For Columbium and Columbium Alloy Bar, Rod, and Wire, Sixth Draft, American Society For Testing and Materials (March 13, 1962).

(4) Proposed ASTM Specifications For Columbium and Columbium Alloy Seamless and Welded Tubes, Sixth Draft, American Society For Testing and Materials (March 13, 1962).

(5) "Columbium and Tantalum Base Alloys For Structural and Nuclear Application", Wah Chang Corp., Vol 1, Rev. 2 (1962).

(6) "Product Specification - Columbium Base Alloys", report from Du Pont, Pigments Department - Metal Products, E. I. du Pont de Nemours and Co., Inc.

(7) "SCb-990 Electron Beam Columbium Alloy" Stauffer Metals Division Data Sheet.

(8) "Haynes Alloy Cb-751", New Product Data, Haynes Stellite Co.

(9) Begley, R. T., "Development of Niobium-Base Alloys", Westinghouse Electric Corp., WADC TR 57-344 (November, 1957).

(10) "Shear Strength Properties of Refractory Metal Fasteners", McDonnell Aircraft Corp., Contract No. AF 33(657)-7749 and BPSN:2(8-7381)-73812, Report 9346, Serial No. 3 (January 10, 1963).

Cb-5Zr

1. Identification of Material

   a. Designation: D-14 (Du Pont)

   b. Chemical composition: Table A-22

   c. Forms available: sheet, strip, plate, bar, and tube hollows[1,2]

TABLE A-22. CHEMICAL REQUIREMENTS FOR D-14 FABRICATED SHAPES[1]

Element	Content, Maximum, weight per cent (a)	(b)
Zr	4.4 min - 5.6 max	4.4 min - 5.6 max
O	0.0400	0.0300
H	0.0020	0.0020
N	0.0100	0.0100
C	0.0100	0.0100
Cb	By difference	By difference

(a) Sheet, strip, plate, rectangular bar, and round bar.
(b) Tube hollows.

2. Physical Properties

a. Melting point: 3950 F[2]

b. Density: 0.310 lb/in.^{3}[2]

c. Thermal expansion: Figure A-36

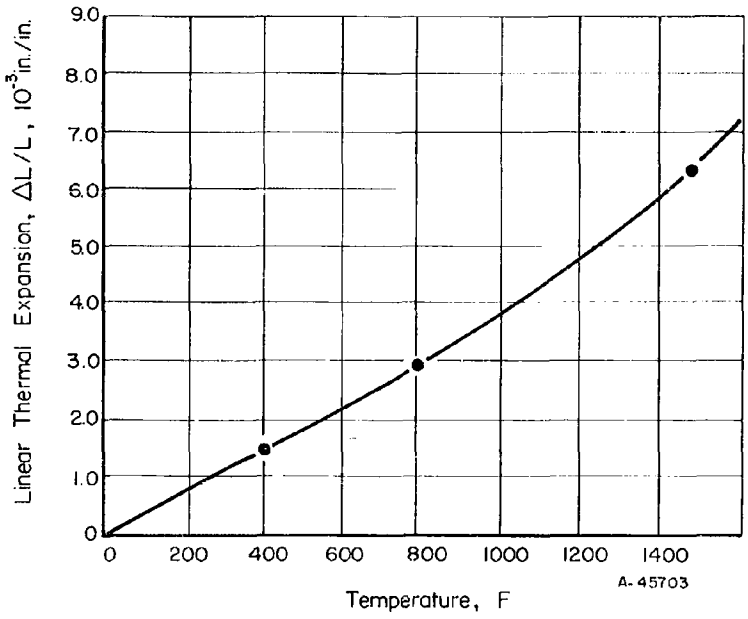


FIGURE A-36. THERMAL EXPANSION OF ARC-MELTED D-14[2]

3. Mechanical Properties

a. Tensile Properties at Room Temperature

Ultimate tensile strength: Table A-23

Tensile yield strength: Table A-23

Elongation: Table A-23

Reduction in Area: Table A-23

Modulus of elasticity: 13.7×10^6 psi[2]

b. Effect of Temperature on Tensile Properties

Ultimate tensile strength: Table A-24
Figure A-37

Elongation: Table A-24
Figure A-37

Modulus of elasticity: decreases linearly with temperature from a value of 13.7×10^6 psi at room temperature to a value of 12.1×10^6 psi at 1600 F[2]

c. Creep and Stress-Rupture Properties

Figure A-38

TABLE A-23. ROOM-TEMPERATURE TENSILE PROPERTIES FOR D-14 FABRICATED SHAPES[a][1]

Comments	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent
		Sheet and Strip[b]		
0.006-in. to 0.020-in., incl., min. values	55	45	10 (2 in.)	--
Over 0.020-in. to 0.187-in., incl., min. values	55	45	12 (2 in.)	--
		Plate and Rectangular Bar[c]		
Typical average	61	53	20 (2-in. or 4D)	--
Probable minimum	50	45	12 (2-in. or 4D)	--
		Round Bar[c]		
Typical average	61	53	45 (4D)	85
Probable minimum	50	45	25 (4D)	50

(a) Test rate 0.005 ± 0.002 inch per inch per minute through 0.6 per cent offset, then 0.05 ± 0.02 inch per inch per minute to failure. Typical analyses 4.4 - 5.0% Zr, <0.0400% O, <0.0020% H, <0.0100% N, and <0.0100% C.
(b) Stress relieved 1 hour at 1950 F.
(c) Recrystallized condition.

TABLE A-24. MINIMUM TENSILE-PROPERTY REQUIREMENTS FOR D-14 STRESS-RELIEVED SHEET AT 2200 F[a][1]

Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1 Inch, per cent
15	10	10

(a) Stress relieved 1 hour 1950 F, 0.006 inch to 0.187 inch, inclusive. Test rate 0.05 ± 0.02 inch per inch per minute. Typical analyses 4.4 - 5.0% Zr, <0.0400% O, <0.0020% H, <0.0100% N, and <0.0100% C.

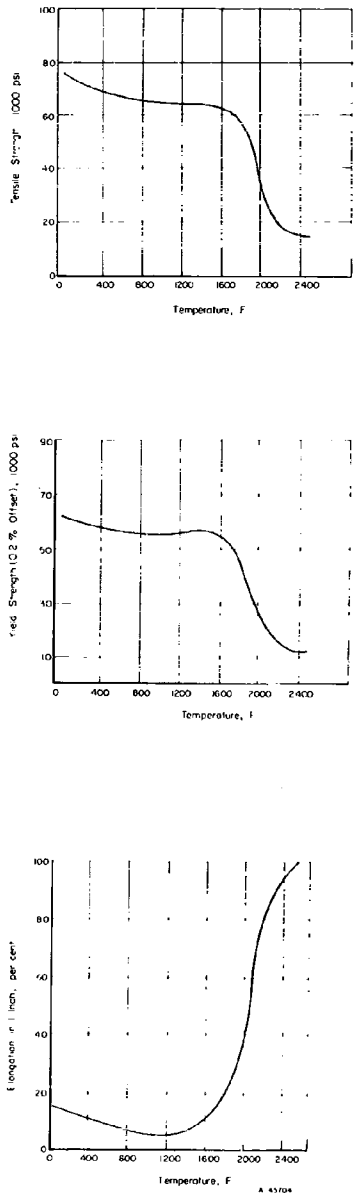


FIGURE A-37. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF ARC-MELTED STRESS-RELIEVED D-14 SHEET (0.040 INCH)[2]

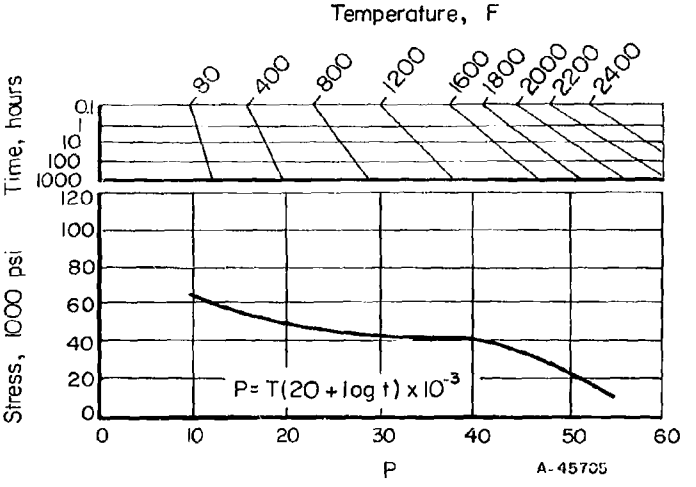


FIGURE A-38. STRESS-RUPTURE CHARACTERISTICS OF ARC-MELTED D-14 IN ARGON FROM ROOM TEMPERATURE TO 2400 F[2]

4. Metallurgical Properties

a. Fabricability: readily fabricated from arc melted ingot using primary breakdown extrusion or forging and subsequent standard conversion to mill shapes[2]

b. Transition temperature: <RT[1,2]

c. Weldability: fusion and resistance weldable by all standard processes including hand TIG welding; in the as-welded condition, fusion welds in sheet can be bent to greater than 2T, provided adequate protection from the atmosphere is maintained during welding[2]

d. Stress-relief temperature: 1 hour at 1950 F[1]

References

(1) "Product Specification - Columbium Base Alloys", report from Du Pont, Pigments Department - Metal Products, E. I. du Pont de Nemours and Co., Inc.

(2) "Du Pont Metal Products. Columbium Product Data", E. I. du Pont de Nemours and Co., Inc., Sheet No. 3 (1963).

Cb-5V

1. Identification of Material

   a. Designation: B-33 (Westinghouse)

   b. Chemical composition: typical analyses are i. licated below[1]

Element	Composition, weight per cent Range	Nominal
V	4.5 - 5.5	5.0
O	0.030 max	0.012
N	0.020 max	0.006
C	0.020 max	0.006
Cb	Remainder	Remainder

   c. Forms available: plate, sheet, strip, foil, bar, wire, tubing, forgings, and extrusions[1]

2. Physical Properties

   a. Melting point: 4310 F[1]

   b. Density: 0.306 lb/in.^{3}[1]

   c. Thermal expansion: Table A-25

   d. Electrical resistivity: 21.8 microhm-cm at RT; 6.64 microhm-cm at -320 F[1]

TABLE A-25. COEFFICIENT OF THERMAL EXPANSION OF B-33[1]

Temperature, C	F	Coefficient of Thermal Expansion 10^{-6} In./In./C	10^{-6} In./In./F
25-250	80-500	7.47	4.15
25-540	80-1000	7.64	4.24
25-815	80-1500	8.06	4.48
25-1095	80-2000	8.49	4.71
25-1365	80-2500	8.90	4.94

3. Mechanical Properties

a. Tensile Properties at Room Temperature

Ultimate tensile strength: Table A-26

Tensile yield strength: Table A-26

Elongation: Table A-26

Modulus of elasticity: 15.8×10^6 psi[1]

b. Effect of Temperature on Tensile Properties

Ultimate tensile strength: Tables A-27 and A-28

Tensile yield strength: Tables A-27 and A-28

Elongation: Tables A-27 and A-28

Modulus of elasticity: 15.0×10^6 psi at 2000 F[1]

c. Creep and Stress-Rupture Properties

Figures A-39 and A-40

d. Other Selected Mechanical Properties

Hardness: for various conditions see below[1]

Condition	Vickers, DPH	Rockwell B	Rockwell C
As rolled	260	--	23
Stress relieved 1 hr 1850 F	200	85	--
Recrystallized 1 hr 2000 F	180	80	--

Bend ductility: for annealed (1 hour 2000 F) sheet[1]

Temperature, F	Minimum Bend Radius, T
80	0-1
-100	1
-200	1
-320	1

TABLE A-26. ROOM-TEMPERATURE TENSILE PROPERTIES OF B-33[a][1]

Condition	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent
As rolled, 90%	129.0	114.5	6
Stress-relieved 1 hr 1850 F	82.5	62.6	26
Recrystallized 1 hr 2000 F	77.6	54.0	32

(a) Test rate 0.005 inch per inch per minute. Nominal analyses 5.0% V, 0.012% O, 0.006% N, and 0.006% C.

TABLE A-27. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF RECRYSTALLIZED B-33[1]

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, 1 inch, per cent
	Recrystallized 1 Hour at 2000 F[a]		
-320	132.0	112.5	33
-150	91.7	74.2	23
75	77.6	54.0	32
300	67.8	46.7	27
600	63.0	39.2	20
800	63.4	39.4	18
2000	30.7	29.2	57
2200	20.7	18.8	47
2400	13.7	13.0	55
2500	12.8	10.8	95
	Recrystallized 1 Hour at 2500 F[b]		
2000	39.2	31.5	12
2200	32.1	27.6	20
2400	24.0	22.7	30
2600	17.6	17.6	30
2800	14.4	13.6	20

(a) Test rate 0.005 inch per inch per minute. Nominal analyses 5.0% V, 0.012% O, 0.006% N, and 0.006% C.

(b) Test rate 0.24 inch per inch per minute.

TABLE A-28. HIGH-TEMPERATURE TENSILE PROPERTIES OF B-33 SHEET (0.060 INCH)[a][2]

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 2 inches, per cent
2750	11.05	8.3	34
	11.45	8.22	27
3100	5.89	4.18	32
	5.59	4.03	31
3400	3.37	2.205	28
	3.29	2.4	24

(a) Test rate 0.003 to 0.007 inch per inch per minute.

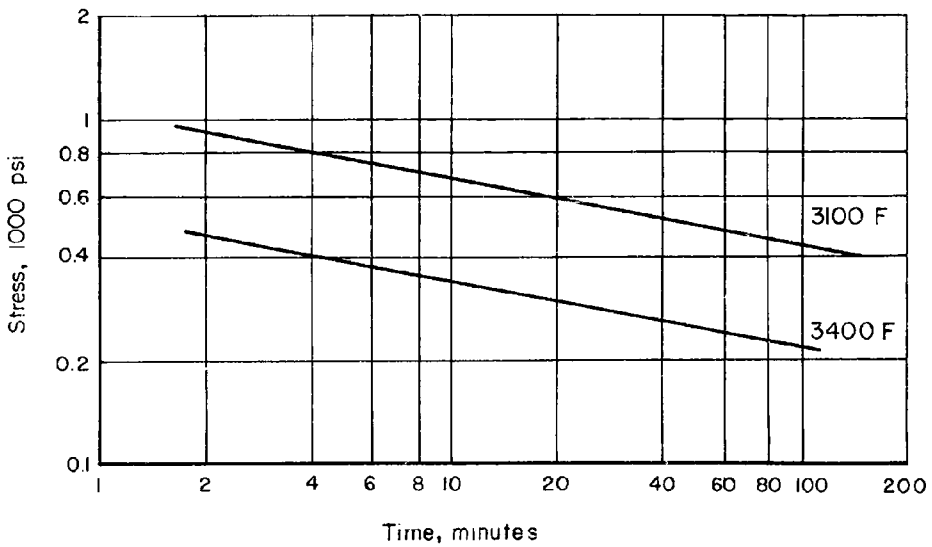


FIGURE A-39. TIME FOR 0.2 PER CENT CREEP AT VARIOUS STRESS LEVELS FOR B-33[2]

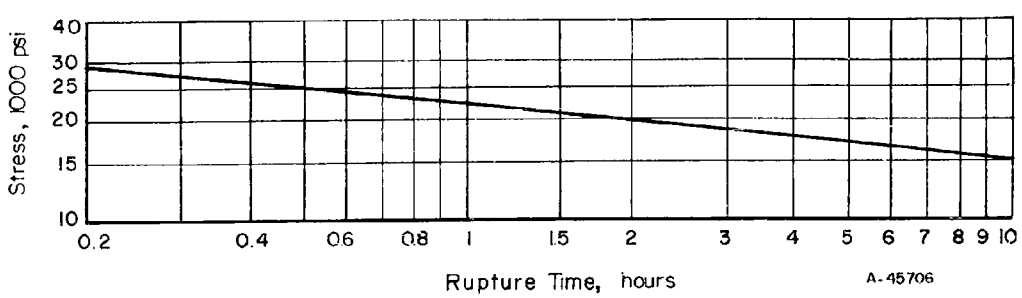


FIGURE A-40. STRESS-RUPTURE CHARACTERISTICS OF B-33 AT 2000 F[1]

Nominal analyses 5.0% V, 0.012% O, 0.0006% N, and 0.0006% C.

4. Metallurgical Properties

a. Fabricability: highly formable alloy which can be punched, blanked, or sheared at room temperature without edge cracking; operations such as bending, brake forming, drawing, and spinning can be performed at room temperature, although they can be accomplished with greater ease slightly elevated temperatures[1]

b. Transition temperature: <-320 F[1]

c. Weldability: the TIG welding process can readily be adapted to form weld joints with essentially the same low-temperature ductility as the base metal; similar results can also be obtained by welding in air using a weld follower with porous bronze diffuser and gas back-up to shield the weld during heating and cooling[1]

d. Stress-relief temperature: 1 hour at 1850 F[1]

e. Recrystallization temperature: 1 hour at 2000 F for material cold worked 80 to 90 per cent[1]

References

(1) "B-33 Columbium (Niobium) Base Alloy Refractory Metal", Westinghouse Electric Corp., Special Technical Data 52-363 (June, 1962).

(2) Moorhead, P. E., "Tensile and Creep Properties of Columbium, Tantalum, and Titanium Alloys at Elevated Temperatures", Bell Aerosystems Company, Report BLR 62-26 (M) (December, 1962).

Cb-10Hf-1Ti-0.5Zr

1. Identification of Material

   a. Designation: C-103 (Wah Chang)

   b. Chemical composition: Typical analyses of arc-cast material[1]

Element	Weight Per Cent
Hf	9-11
Ti	0.7-1.3
Zr	<0.7
O	<0.0300
N	<0.0300
H	<0.0020
C	<0.0100
Cb	Balance

   c. Forms available: ingot and most mill products[1]

2. Physical Properties

   a. Density: 0.32 lb/in.^{3}

3. Mechanical Properties

   a. Tensile Properties at Room Temperature

      Ultimate tensile strength: Table A-29

      Tensile yield strength: Table A-29

      Elongation: Table A-29

      Modulus of elasticity: 12.6×10^6 psi[1]

   b. Effect of Temperature on Tensile Properties

      Ultimate tensile strength: Table A-30

      Tensile yield strength: Table A-30

      Elongation: Table A-30

      Modulus of elasticity: average values from 5 tensile tests[1]

Temperature, F	Modulus of Elasticity, 10^6 psi
RT	12.6
2500	6.3
2700	3.6
3000	1.5

c. Other Selected Mechanical Properties

Bend ductility: for various conditions at room temperature[1]

Condition	Bend Ductility
As cold rolled	120 degree 1 T
Stress relieved 1 hr 1600 F	120 degree 1/2 T
Recrystallized 1 hr 2200 F	120 degree 1/2 T
Recrystallized 1 hr 2800 F	120 degree 1/2 T

Impact: charpy notched impact data on as-rolled material[1]

Temperature, F	Impact Fracture Strength, ft-lb
RT	148, 159
-100	79, 82

TABLE A-29. ROOM-TEMPERATURE TENSILE PROPERTIES OF ARC-CAST C-103 SHEET[a][1]

Condition	Sheet Thickness, inch	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1 Inch, per cent
Cold rolled	0.030	105.2 (L) 107.7 (T)	96.6 (L) 93.6 (T)	4.5 (L) 4 (T)
Stress relieved 1 hr 1600 F	0.040	93.5	88.0	9
Recrystallized 1 hr 2400 F	0.030	58.8	50.4	26

(a) Typical analyses 9-11% Hf, 0.7-1.3% Ti, <0.7% Zr, 0.0300% O, <0.0300% N, <0.0020% H, <0.0100% C, bal Cb.

TABLE A-30. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF ARC-CAST C-103 SHEET[a][1]

Temperature, F	Direction	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1 Inch, per cent
		Cold Rolled, 0.030 Inch		
RT	L	105.2	96.6	4.5
	T	107.7	93.6	4
2000	L	34.2	23.5	39
	T	31.0	26.9	35
2500	L	12.9	11.3	87
	T	13.0	11.4	80
		Stress Relieved 1 Hour at 1600 F, 0.040 Inch		
RT	L	93.5	88.0	9
2000	L	26.4	18.2	63
2500	L	11.65	10.55	>75
2700	L	8.1	7.3	>73
		Recrystallized 1 Hour at 2400 F, 0.030 Inch		
RT	L	58.8	50.4	26
2000	L	27.3	18.4	45
2500	L	12.0	10.3	>70
2700	L	9.5	8.6	>70
3000	L	5.0	4.2	>70

(a) Typical analyses 9-11% Hf, 0.7-1.3% Ti, <0.7% Zr, 0.0300% O, 0.0300% N, <0.0020% H, <0.0100% C, bal Cb.

4. Metallurgical Properties

a. Fabricability: arc-melted ingot can readily be extruded to sheet bar at elevated temperatures; following a recrystallization anneal material is rolled at 800 F to about 0.1 inch, then rolled at room temperature to final size[1]

b. Transition temperature: <-320 F for stress-relieved (1 hour at 1600 F) material[1]

c. Weldability: can readily be welded by TIG welding techniques; weld metal ductility duplicates base metal ductility for both longitudinal and transverse samples at room temperature[1]

d. Stress-relief temperature: 1 hour at 1600 F[1]

e. Recrystallization temperature: for sheet (0.030 inch) material exposed 1 hour at indicated temperature[1]

Temperature, F	Recrystallization, per cent
1600	0
1900	50
2200	100, ASTM 7

Reference

(1) "Columbium and Tantalum Base Alloys For Structural and Nuclear Application", Wah Chang Corp., Vol 1, Rev. 2 (1962).

Cb-10Ta-10W

1. Identification of Material

   a. Designation: SCb-291 (Stauffer)

   b. Chemical composition: typical analyses of electron-beam-melted material[1]

Element	Weight Per Cent
Cb	80
Ta	9-11
W	9-11
O	0.0090
N	0.0100
C	0.0060

   c. Forms available; ingot, billet, bar, plate, sheet, foil, and tube[1]

2. Physical Properties

   a. Melting point: 4710 F[1]

   b. Density: 0.347 lb/in.^{3}[2]

3. Mechanical Properties

   a. Tensile Properties at Room Temperature

      Ultimate tensile strength: Tables A-31 and A-32

      Tensile yield strength: Tables A-31 and A-32

      Elongation: Tables A-31 and A-32

      Reduction in area: Table A-31

   b. Effect of Temperature on Tensile Properties

      Ultimate tensile strength: Tables A-33 and A-34

      Tensile yield strength: Tables A-33 and A-34

      Elongation: Tables A-33 and A-34

   c. Creep and Stress-Rupture Properties

      Table A-35
      Figure A-41

d. Other Selected Mechanical Properties

Hardness: for various forms[1]

Form	Hardness, R_G
Forged bar	70
As-rolled sheet	80
Annealed sheet	64

TABLE A-31. TYPICAL ROOM-TEMPERATURE TENSILE PROPERTIES OF ELECTRON-BEAM-MELTED SCb-291[a][1]

Property	Forged Bar	Annealed Bar	As-Rolled Sheet	Annealed Sheet
Tensile Strength, 1000 psi	[illegible]	66	12[illegible]	88
Yield Strength (0.2% Offset), 1000 psi	66	51	--	74
Elongation in 2 Inches, per cent	31	20	8	22
Reduction in Area, per cent	78	93	--	--

(a) Typical analyses 80% Cb, 9-11% Ta, 9-11% W, 0.0090% O, 0.0100% N, and 0.0060% C.

TABLE A-32. ROOM-TEMPERATURE TENSILE PROPERTIES OF SCb-291 REROLL STOCK AND FINISHED FOIL[a][3]

Coil Identification	Gage, inch	Recrystallization, per cent	ASTM Grain Size	Test Direction	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 2 Inches, per cent
			Reroll Foil Stock				
291-1, -2	0.030	100	6.5	L	64.1	52.2	28.5
				T	66.9	53.5	29.0
			Finished Foil				
291-1	0.006	100	8.5	L	68.9	57.0	26.5
				T	72.0	60.1	21.0
291-2	0.006	100	7.5	L	69.1	57.9	19.5
				T	68.5	61.2	18.0

(a) Test rate 0.005 inch per inch per minute to 0.2 per cent yield, and then 0.05 inch per inch per minute to failure. Analyses are as follows:

Coil Identification	Gage, inch	Analyses: Weight, per cent W	Ta	PPM O	N	C	H
		Reroll Foil Stock					
291-1, -2	0.030	10.3	10.1	<50	16	170	<5
		Finished Foil					
291-1	0.006	--	--	95	46	90	<5
291-2	0.006	--	--	100	50	95	<5

TABLE A-33. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF ANNEALED ELECTRON-BEAM-MELTED SCb-291 SHEET[a][2]

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 2 Inches, per cent	Number of Tests
RT	75	60	25	--
800	60	50	22	8
1000	52	40	23	2
1200	48	37	22	--
1600	45	35	20	--
1800	39	30	22	8
2000	32	24	24	5
2200	27	20	22	7
2400	21	15	25	6
2500	18	13	24	9
2600	16	11	24	4
2800	12	8.5	22	14
3000	10	7	23	15
3200	8	6	24	7
3400	6.5	4.8	25	4

(a) Typical analyses 80% Cb, 9-11% Ta, 9-11% W, 0.0090% O, 0.0100% N, and 0.0060% C.

TABLE A-34. HIGH TEMPERATURE TENSILE PROPERTIES OF ELECTRON-BEAM-MELTED SCb-291 SHEET (0.060 INCH)[a][4]

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 2 Inches, per cent
2800	11.99	8.3	21.5
3100	9.03	6.34	24.0
	8.7	6.07	23.5
3400	6.57	4.72	25.0
	6.48	4.87	25.5

(a) Test rate 0.003 to 0.007 inch per inch per minute.

TABLE A-35. STRESS-RUPTURE PROPERTIES OF COLD-ROLLED ELECTRON-BEAM-MELTED SCb-291 SHEET[a][1]

Temperature, F	Stress, 1000 psi	Time to Rupture, hours
2730	7.8	2.5
2970	5.0	2.4
3200	3.8	2.1

(a) Typical analyses 80% Cb, 9-11% Ta, 9-11% W, 0.0090% O, 0.0100% N, and 0.0060% C.

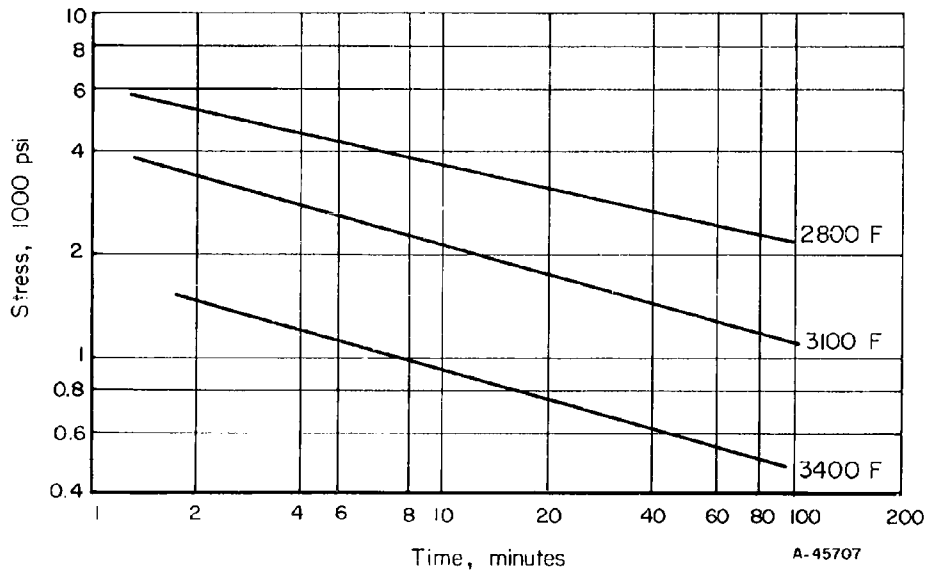


FIGURE A-41. TIME FOR 0.2 PER CENT CREEP AT VARIOUS STRESS LEVELS FOR ELECTRON-BEAM MELTED SCb-291[4]

4. Metallurgical Properties

a. Fabricability: ingots are heated to 2200 F for forging; after 25 to 30 per cent reduction, forging temperatures may be reduced to 1700 to 2000 F; forged sheet bars are rolled to intermediate thickness at 500 to 700 F; finish rolling reductions of 60 to 70 per cent are attainable at room temperature[1]

b. Transition temperature: -30 F Charpy V-notch impact transition[1]

c. Weldability: electron-beam-welding produces welds that can be bent 180 degress without cracking; shielded-arc inert-gas welding allows welds approaching the quality of electron-beam welds, depending upon the purity of the welding atmosphere[1]

d. Stress-relief temperature: 1/2 to 1 hour at 1800 F[1]

e. Recrystallization temperature: 1 hour at 2100 to 2200 F[1]

References

(1) "SCb-291 Electron Beam Columbium Alloy", Stauffer Metals Division Data Sheet (February, 1962).

(2) "SCb-291, Cb-10Ta-10W, Progress Report", Stauffer Metals Divison Data Sheet (January, 1963).

(3) Personal communication with G. P. Trost, Metals and Controls Inc., regarding "Development of Optimum Processing Parameters for Refractory Metal Foil," Contract No. AF 33(657)-9384 (June, 1963).

(4) Moorhead, P. E., "Tensile and Creep Properties of Columbium, Tantalum, and Titanium Alloys at Elevated Temperatures", Bell Aerosystems Co., BLR 62-26 (M) (December, 1962).

Cb-28Ta-10W-1Zr

1. Identification of Material

   a. Designation: FS-85 (Fansteel)

   b. Chemical composition: see below[1]

Element	Weight Per Cent Minimum	Weight Per Cent Maximum
Ta	26	29
W	10	12
Zr	0.6	1.1
C	--	0.0100
O	--	0.0300
N	--	0.0150
H	--	0.0010
Fe	--	0.0100
Si	--	0.0100
Cb	Balance	

   c. Forms available: ingot, plate, sheet, strip, foil, rod, wire, welded tubing, and fabricated parts[1]

2. Physical Properties

   a. Melting point: 4695 F[1]

   b. Density: 0.383 lb/in.^{3}[1]

   c. Thermal expansion: Figure A-42

   d. Thermal conductivity: see below[1]

Temperature, C	Thermal Conductivity, cal/(cm^2)(sec)(C/cm)
150	0.09
205	0.09
260	0.10
315	0.10

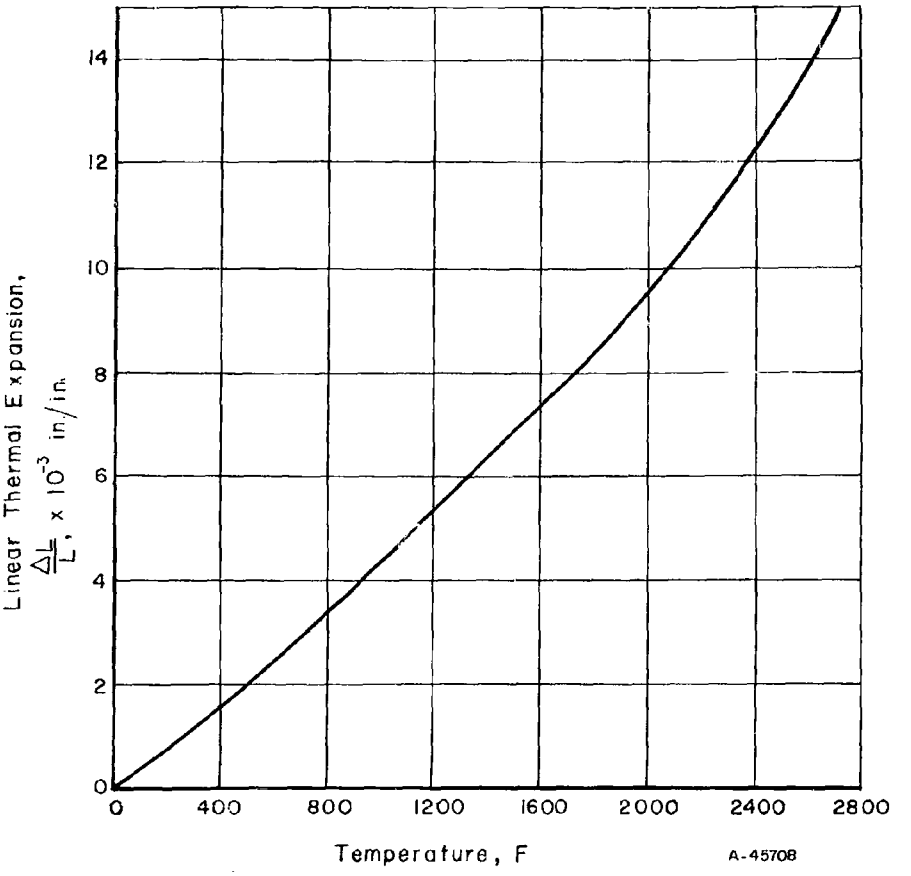


FIGURE A-42. LINEAR THERMAL EXPANSION OF FS-85[1]

3. Mechanical Properties

a. Tensile Properties at Room Temperature

Ultimate tensile strength: Tables A-36 through A-38

Tensile yield strength: Tables A-36 through A-38

Elongation: Tables A-36 through A-38

Reduction in area: Table A-36

Modulus of elasticity: 20×10^6 psi[1]

b. Effect of Temperature on Tensile Properties

Ultimate tensile strength: Tables A-39 and A-40
Figure A-43

Tensile yield strength: Tables A-39 and A-40
Figure A-43

Elongation: Tables A-39 and A-40
Figure A-43

Reduction in area: Table A-39

Modulus of elasticity: see below[3]

Temperature, F	Modulus of Elasticity, 10^6 psi
RT	20
1800	18
2000	18
2200	16
2800	15
2900	12
3000	12

c. Notched tensile properties: for edge-notched sheet (0.040 inch)[6]

Condition	Notch Radius, inch	Net Fracture Strength, 1000 psi	Length of Rapid Crack, inch	Shear Fracture in Area of Rapid Crack, per cent
Stress relieved	0.00087	68.7	0	100
Recrystallized	0.0013	53.3	0	100

d. Creep and Stress-Rupture Data

Table A-41

e. Other Selected Mechanical Properties

Bend ductility: Table A-42

TABLE A-36. ROOM-TEMPERATURE TENSILE PROPERTIES OF FS-85 SHEET (0.030 INCH)[a][2]

Condition	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1 Inch, per cent	Reduction in Area, per cent
Stress relieved, as received	119.4	109.5	10.5	42.9
	120.4	106.8	11.0	47.6
	120.5	104.8	11.0	42.8
Recrystallized 1 hr 2300 F	86.9	69.5	21.5	46.7
	85.3	69.2	22.0	54.0
	85.6	69.4	23.0	54.7
Recrystallized and Cr-Ti-Si coated	84.2	68.4	18.0	32.8
	83.8	68.6	17.5	32.5
	80.4	65.7	16.0	25.1

(a) Test rate 0.020 inch per inch per minute. Analyses 27.92% Ta, 10.0% W, 0.98% Zr, 0.0150% O, 0.0020% N, and 0.0250% C.

TABLE A-37. ROOM TEMPERATURE TENSILE PROPERTIES OF FS-85 SHEET[a][3]

Condition	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 2 Inches, per cent
50 Per Cent Cold Worked, 0.040 Inch			
Stress relieved 1 hr 1830 F	105.0	95.4	14
94.1 Per Cent Cold Worked, 0.063 Inch			
As worked	130.0	--	4.0
	128.0	119.0	6.0
Stress relieved 1 hr 1830 F	109.0	97.6	14
Recrystallized 1 hr 1830 F	78.9	66.4	33

(a) Test rate 0.05 inch per minute crosshead speed. Analyses 60.54% Cb, 27.12% Ta, 11.8% W, 0.53% Zr, 0.005% C, 0.002% O, and 0.003% N.

TABLE A-38. EFFECT OF TEST DIRECTION ON THE ROOM-TEMPERATURE TENSILE PROPERTIES OF FS-85 SHEET[4]

Test Direction	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1 Inch, per cent
L	95.5	76.5	25.5
	94.0	77.7	24.5
	94.0	80.0	25.5
T	95.0	79.5	18.0
	86.0	69.0	20.0
	99.0	80.0	21.5

TABLE A-39. TENSILE PROPERTIES OF RECRYSTALLIZED FS-85 SHEET (0.030 INCH) FROM ROOM TEMPERATURE TO 2600 F[a][2]

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1 Inch, per cent	Reduction in Area, per cent
RT	86.9	69.5	21.5	46.7
	85.3	69.2	22.0	54.0
	85.6	69.4	23.0	54.7
400	68.0	53.1	21.2	81.9
	68.0	52.0	20.7	71.5
800	53.3	38.8	17.5	77.8
	54.9	40.9	19.7	92.2
1200	63.1	46.0	15.3	81.2
	61.8	39.1	13.2	77.3
1600	51.8	32.4	17.7	94.7
	53.0	35.3	15.9	64.1
1800	45.0	30.0	17.7	71.5
	44.8	34.6	16.1	72.0
2000	36.0	29.5	28.8	73.3
	36.4	29.4	24.8	77.8
2300	25.2	21.5	39.1	89.2
	24.9	22.0	33.8	86.4
2500	17.4	16.3	50.4	96.1
	16.5	15.6	57.3	92.5
2600	14.7	14.3	78.1	96.7
	14.5	14.1	80.2	97.5

(a) Recrystallized 1 hour at 2300 F. Test rate 0.020 inch per inch per minute. Analyses 27.92% Ta, 10.0% W, 0.98% Zr, 0.0150% O, 0.0020% N, and 0.0250% C.

TABLE A-40. HIGH-TEMPERATURE TENSILE PROPERTIES OF FS-85 STRESS-RELIEVED SHEET[1]

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 2 Inches, per cent
3000	10.7	10.4	<80
3200	8.6	8.3	<80
3500	6.2	5.8	<80
3970	2.9	2.9	99

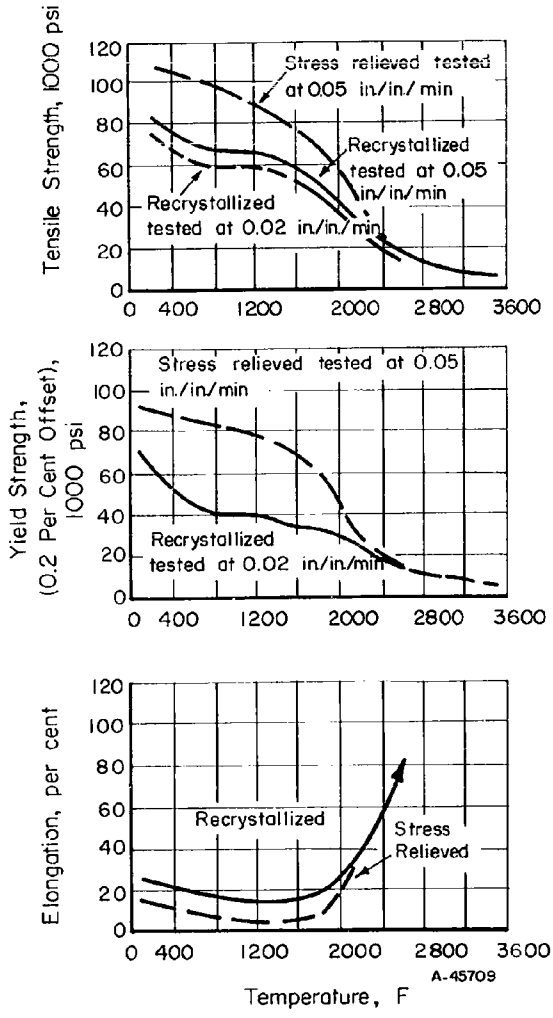


FIGURE A-43. EFFECT OF TEMPERATURE ON THE TYPICAL TENSILE PROPERTIES OF FS-85[5]

Nominal composition 26-29% Ta, 10-12% W, 0.6-1.1% Zr, <0.0100% C, <0.0300% O, <0.0150% N, and <0.0010% H.

TABLE A-41. CREEP AND STRESS-RUPTURE DATA FOR FS-85 SHEET[3]

Temperature, F	Stress, 1000 psi	Secondary Creep Rate, in./in./hr	Rupture Time, hours
	50 Per Cent Cold Worked, 0.040 Inch		
2000	17	3.21×10^{-4}	>158
	19.8	1.71×10^{-3}	--
	20	3.63×10^{-4}	--
	27	6.06×10^{-3}	--
2200	10	$<8.45 \times 10^{-4}$	--
	12	1.19×10^{-3}	--
	14	2.46×10^{-3}	--
	16	5.25×10^{-3}	--
	18	1.06×10^{-2}	--
	19	1.32×10^{-2}	10.42
	20	2.20×10^{-2}	--
2400	13	1.85×10^{-2}	9.28
2600	10	1.88×10^{-2}	9.29
	94.1 Per Cent Cold Worked, 0.063 Inch		
1800	35	9.30×10^{-3}	6.51
2000	20	4.62×10^{-3}	23.78
	27	--	2.33
2200	19	5.13×10^{-2}	2.72
2400	13	3.99×10^{-2}	4.93
	13	3.24×10^{-2}	6.12
	12[a]	--	11.21
2600	10	4.14×10^{-2}	>4.7
	10[a]	3.45×10^{-2}	5.01

(a) Annealed 1 hour at 2400 F.

TABLE A-42. BEND-DUCTILITY DATA FOR FS-85 SHEET (0.040 INCH)[a][6]

Condition	Temperature, F	Ram Radius, T	Successful Full Bend Angle, degrees
Cold rolled 50%	RT	1T	113-125
	-320	4T[b]	110-114
		4T	127-131
		2T	121
		1T[b]	109-110
		1T	89-90[c]
Stress relieved	RT	1T	127-128
	-320	4T	135
		1T	121-123
Recrystallized	RT	1T	130-131
	-320	4T	140
		1T	121-124

(a) Test rate 10 inches per minute. Analyses 27.68% Ta, 10.89% W, 0.93% Zr, 0.002% C, and 0.005% O.
(b) Test rate 0.1 inch per minute.
(c) Not a full bend angle.

4. Metallurgical Properties

a. Fabricability: after high temperature breakdown using conventional practices, final rolling, forming, blanking, spinning and drawing can be readily performed at room temperature[1]

b. Transition temperature: <-320 F for cold-rolled, stress-relieved, or recrystallized sheet (0.040 inch)[6]

c. Weldability: may be welded using conventional TIG techniques; welded sheet, both annealed and stress relieved, exhibits a 1T bend at -125 F[1]

d. Stress-relief temperature: 1 hour at 1830 for sheet material[3]

Figure A-44

e. Recrystallization temperature: 1 hour at 2400 F for sheet material[3]

Figure A-44

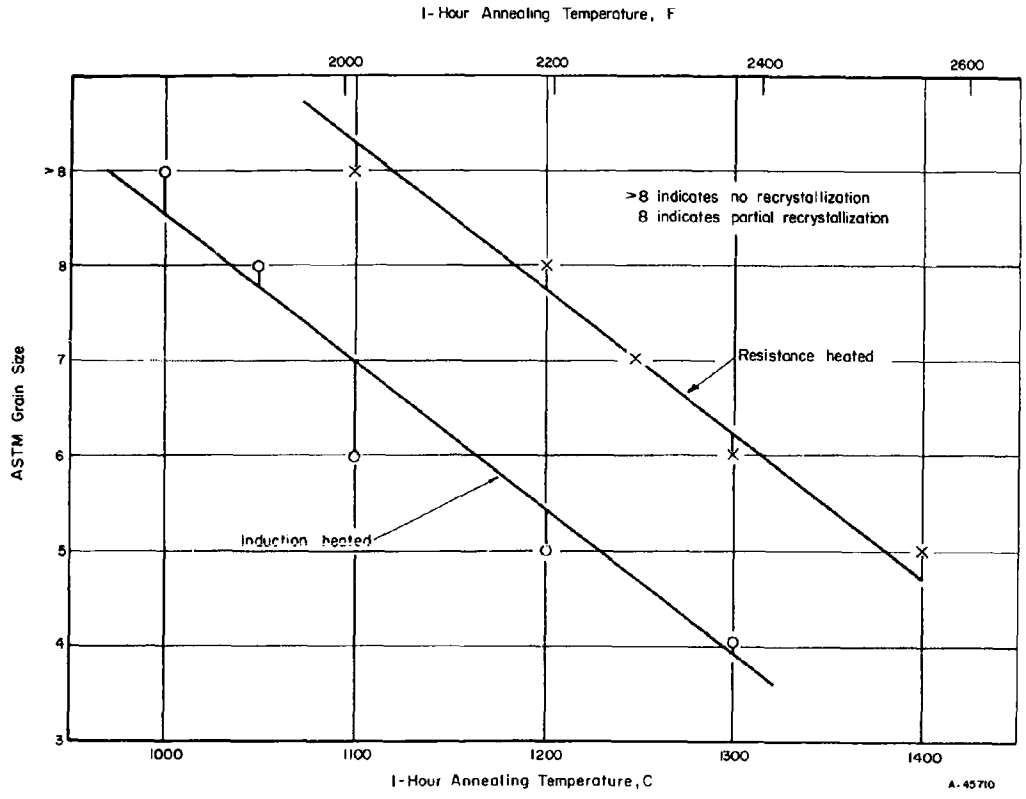


FIGURE A-44. GRAIN SIZE AS FUNCTION OF ANNEALING TEMPERATURE FOR FS-85 SHEET(6)

References

(1) "Fansteel 85 Metal", Fansteel Metallurgical Corp., TD-823-C.

(2) Gadd, J. D., "Design Data Study for Coated Columbium Alloys", Thompson Ramo Wooldridge Inc., Final Summary Technical Report prepared under Contract NOw 62-0098-C (January 31, 1963).

(3) Gentry, W. O., Michael, A. B., "Properties of Some Columbium-Rich Alloys in the Columbium-Tantalum-Tungsten-Zirconium System", Fansteel Metallurgical Corp., paper presented at AIME High Temperature Materials Conference, Cleveland (April 26-27, 1961).

(4) Data presented before the Alloy Selection Group of the MAB by Fansteel Metallurgical Corp. (November 2, 1962).

(5) Jaeger, R. O., "Fansteel Metallurgy", Fansteel Metallurgical Corp., (January - February, 1963).

(6) "Metallurgical Data on FS-85 Alloy (Ingot 85D333)", Fansteel Metallurgical Corp., Interim Report presented before the Selection Subpanel of the Refractory Metals Sheet Rolling Panel, MAB, Washington (March 26, 1962).

Cb-32Ta-1Zr

1. Identification of Material

   a. Designation: FS-82 (Fansteel)

   b. Chemical composition: typical analyses for arc-cast material[1]

Element	Weight Per Cent
Ta	33
Zr	1.0
O	<0.0300
C	<0.0100
N	<0.0200
H	<0.0020

   c. Forms available: ingot and most mill products

2. Physical Properties

   a. Melting point: 4570 F[2]

   b. Density: 0.367 lb/in.^{3} (calculated)

   c. Thermal expansion: Figures A-45 and A-46

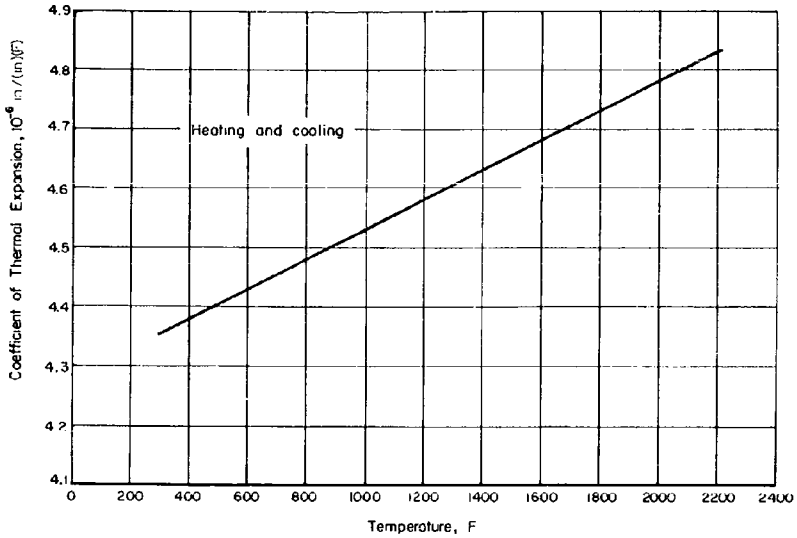


FIGURE A-45. MEAN COEFFICIENT OF THERMAL EXPANSION OF FS-82[3]

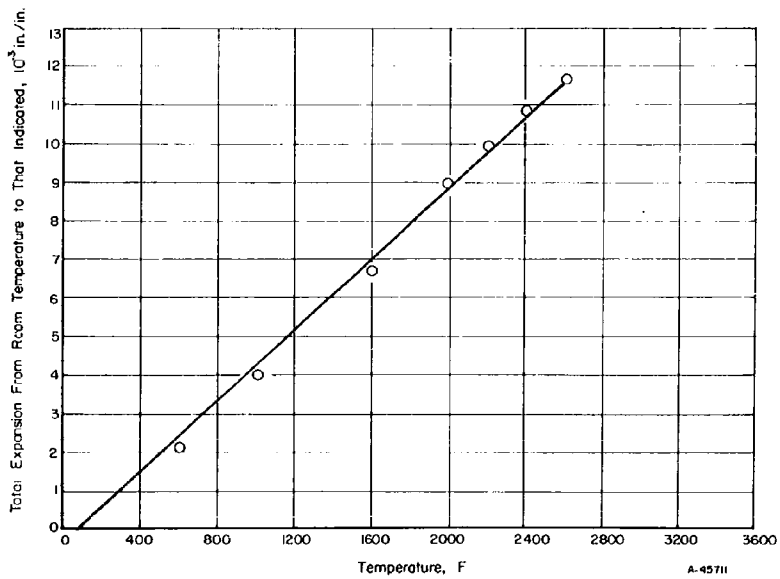


FIGURE A-46. THERMAL EXPANSION OF STRESS-RELIEVED FS-82 SHEET (0.040 INCH)[4]

Stress relieved 1 hour at 1900 F.

3. Mechanical Properties

a. Tensile Properties at Room Temperature

Ultimate tensile strength: Tables A-43 through A-45

Tensile yield strength: Tables A-43 through A-45

Elongation: Tables A-43 through A-45

Modulus of elasticity: 17×10^6 psi[5]
$\sim 18 \times 10^6$ psi[4]

b. Effect of Temperature on Tensile Properties

Ultimate tensile strength: Tables A-46 through A-48
Figures A-47 and A-48

Tensile yield strength: Tables A-46 through A-48
Figure A-47

Elongation: Tables A-46 through A-48
Figure A-47

Modulus of elasticity: Figure A-47

c. Notched Tensile Properties

Table A-49

d. Creep and Stress-Rupture Properties

Tables A-50 and A-51
Figures A-49 through A-51

e. Other Selected Mechanical Properties

Shear strength: for stress-relieved (1 hour 1900 F) sheet material[3]

Temperature, F	Shear Strength, 1000 psi	Per Cent of Tensile Strength
RT	76.0	93.0
	73.6	90.3
2500	7.66	64.6
	8.15	68.8

Bearing strength: Table A-52

TABLE A-43. SOME SELECTED ROOM-TEMPERATURE TENSILE PROPERTIES OF FS-82

Condition	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent	Reference
Stress-relieved sheet (1 hr 1900 F, 0.125 inch)[a]	90.0	80.0	19.7	(3)
	88.0	79.5	19.5	(3)
Stress-relieved sheet (1 hr 1900 F, 0.020 inch)[b]	82.7	71.8	11.3	(3)
	80.7	65.7	11.3	(3)
	81.4	71.7	11.3	(3)
Recrystallized material	55.0	37.0	24	(1)

(a) Test rate 0.2 inch per minute crosshead speed.
(b) Test rate 0.005 inch per inch per minute to yield, then 0.03 inch per inch per minute to fracture.

TABLE A-44. EFFECT OF TEST DIRECTION ON THE TENSILE PROPERTIES OF FS-82 SHEET AT ROOM-TEMPERATURE[3]

Sheet Thickness, inch	Property	Test Direction		
		Longitudinal	Transverse	45-degree
0.010	Tensile Strength, 1000 psi	91	103	86
	Yield Strength (0.2% Offset), 1000 psi	81	93	81
	Elongation in 3/4 Inch, per cent	8	8	10
0.017	Tensile Strength, 1000 psi	67	68	62
	Yield Strength (0.2% Offset), 1000 psi	53	50	50
	Elongation in 3/4 Inch, per cent	13	12	18
0.018	Tensile Strength, 1000 psi	68	69	62
	Yield Strength (0.2% Offset), 1000 psi	57	52	51
	Elongation in 3/4 Inch, per cent	12	10	16
0.020	Tensile Strength, 1000 psi	68-89	68-94	60-88
	Yield Strength (0.2% Offset), 1000 psi	51-81	49-81	54-80
	Elongation in 3/4 Inch, per cent	11-17	10-18	12-18
0.070	Tensile Strength, 1000 psi	108	115	107
	Yield Strength (0.2% Offset), 1000 psi	99	101	99
	Elongation in 3/4 Inch, per cent	15	10	14

TABLE A-45. EFFECT OF STRAIN RATE ON THE ROOM-TEMPERATURE TENSILE PROPERTIES OF STRESS-RELIEVED FS-82 SHEET (0.125 INCH)[a][3]

Crosshead Speed, inch per minute	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1 Inch, per cent
0.2	89.5	80.0	19.6
5	80.0	83.9	15.0
10	92.6	92.5	15.0

(a) Stress relieved 1 hour at 1900 F.

TABLE A-46. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF STRESS-RELIEVED FS-82 SHEET (0.120 INCH)[a][3]

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1 Inch, per cent
RT	90.0	80.0	19.7
	88.0	79.5	19.5
1600	69.0	57.0	14.1
	66.5	60.0	15.5
2000	50.5	44.5	28.2
	50.8	42.5	24.0
2500	14.2	12.0	76.0
	14.5	12.3	68.0

(a) Stress relieved 1 hour at 1900 F. Test rate 0.2 inch per minute crosshead speed.

TABLE A-47. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF STRESS-RELIEVED FS-82 SHEET (0.020 INCH)[a][3]

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 3/4 Inch, per cent
RT	82.7	71.8	11.3
	80.7	65.7	11.3
	81.4	71.7	11.3
1000	74.6	63.7	3.8
	84.0	77.5	3.8
	75.0	66.4	2.5
1600	62.7	47.8	10.0
	66.9	54.5	7.5
	64.6	53.9	3.8
2500	13.3	13.1	65.0
	10.4	8.7	41.0

(a) Stress relieved 1 hour at 1900 F. Test rate 0.005 inch per inch per minute to yield, then 0.03 inch per inch per minute to fracture.

TABLE A-48. EFFECT OF TEST DIRECTION ON THE TENSILE PROPERTIES OF FS-82 SHEET AT 2200 F[3]

Sheet Thickness, inch	Property	Test Direction		
		Longitudinal	Transverse	45 Degree
0.010	Tensile Strength, 1000 psi	17	15	16
	Yield Strength (0.2% Offset), 1000 psi	8	10	10
	Elongation in 3/4 Inch, per cent	63	58	82
0.017	Tensile Strength, 1000 psi	14	14	18
	Yield Strength (0.2% Offset), 1000 psi	10	10	9
	Elongation in 3/4 Inch, per cent	83	58	76
0.018	Tensile Strength, 1000 psi	15	15	15
	Yield Strength (0.2% Offset), 1000 psi	9	9	10
	Elongation in 3/4 Inch, per cent	73	63	66
0.020	Tensile Strength, 1000 psi	18-30	19-34	20-26
	Yield Strength (0.2% Offset), 1000 psi	9-19	10-21	10-16
	Elongation in 3/4 Inch, per cent	28-72	20-52	26-58
0.070	Tensile Strength, 1000 psi	23	35	30
	Yield Strength (0.2% Offset), 1000 psi	13	20	18
	Elongation in 3/4 Inch, per cent	54	30	38

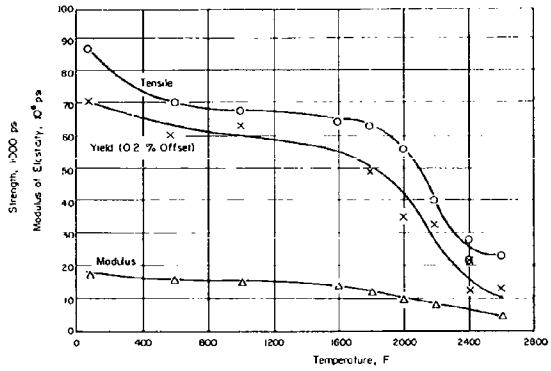


FIGURE A-47. EFFECT OF TEMPERATURE ON THE STRENGTH AND MODULUS OF STRESS-RELIEVED FS-82 SHEET (0.040 INCH) IN HELIUM[4]

Stress relieved 1 hour at 1900 F.

Test rate 0.003-0.005 inch per inch per minute to yield, then 0.02-0.04 inch per inch per minute to fracture.

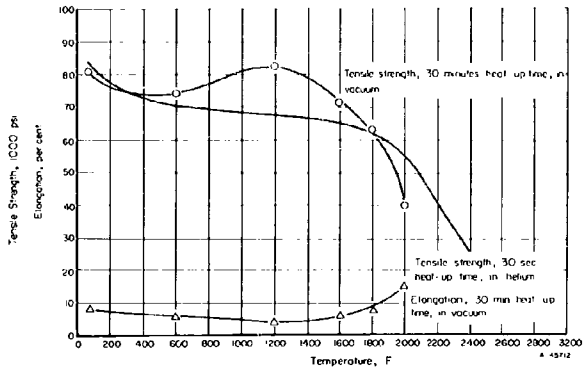


FIGURE A-48. EFFECT OF TEMPERATURE AND HEAT-UP TIME PRIOR TO TEST ON THE STRENGTH AND DUCTILITY OF STRESS-RELIEVED FS-82 SHEET (0.040 INCH)[4]

Stress relieved 1 hour at 1900 F.

Tests conducted in vacuum at 0.05 inch per minute crosshead speed. Tests conducted in helium at 0.003-0.005 inch per inch per minute to yield, then 0.02-0.04 inch per inch per minute to fracture.

TABLE A-49. ROOM-TEMPERATURE NOTCHED TENSILE PROPERTIES OF STRESS-RELIEVED FS-82 SHEET (0.020 INCH)[(a)(3)]

Notch Radius, inch	Notch Width, inch	K_t	Notched Tensile Strength, 1000 psi	Elongation in 3/4 Inch, per cent	Notched/Unnotched Strength Ratio
0.007	0.419	5.7	81.6	3.5	1.0
			82.1	3.0	1.05
0.003	0.420	(b)	77.0	3.5	0.94
0.004	0.420	7.3	81.9	3.0	1.0

(a) Stress relieved 1 hour at 1900 F.
(b) Radii of notch considerably different on opposite sides of specimen; K_t = 8.3 on sharp side.

TABLE A-50. STRESS-RUPTURE DATA FOR STRESS-RELIEVED FS-82 SHEET (0.070 INCH) AT 2000 AND 2500 F[(a)(3)]

Temperature, F	Stress, 1000 psi	Rupture Life, hour	Elongation, per cent
2000	20.0	1.6	37
	18.0	0.6	40
	10.0	44.7	47
2500	5.0	14.4	58
	4.0	67.0	74
	3.0	278	56

(a) Stress relieved 1 hour at 1900 F.

TABLE A-51. RUPTURE STRENGTHS OF STRESS-RELIEVED FS-82 SHEET (0.125 INCH)[a][3]

Temperature, F	Stress to Produce Rupture, 1000 psi, at Indicated Time, hours		
	1	10	100
1600	58	49	38
2000	26	19	14.5
2100	21	15.5	11
2200	16	12	8.5
2500	7.5	5.2	3.5

(a) Stress relieved 1 hour at 1900 F. Data taken from Larson-Miller plot, Figure A-50.

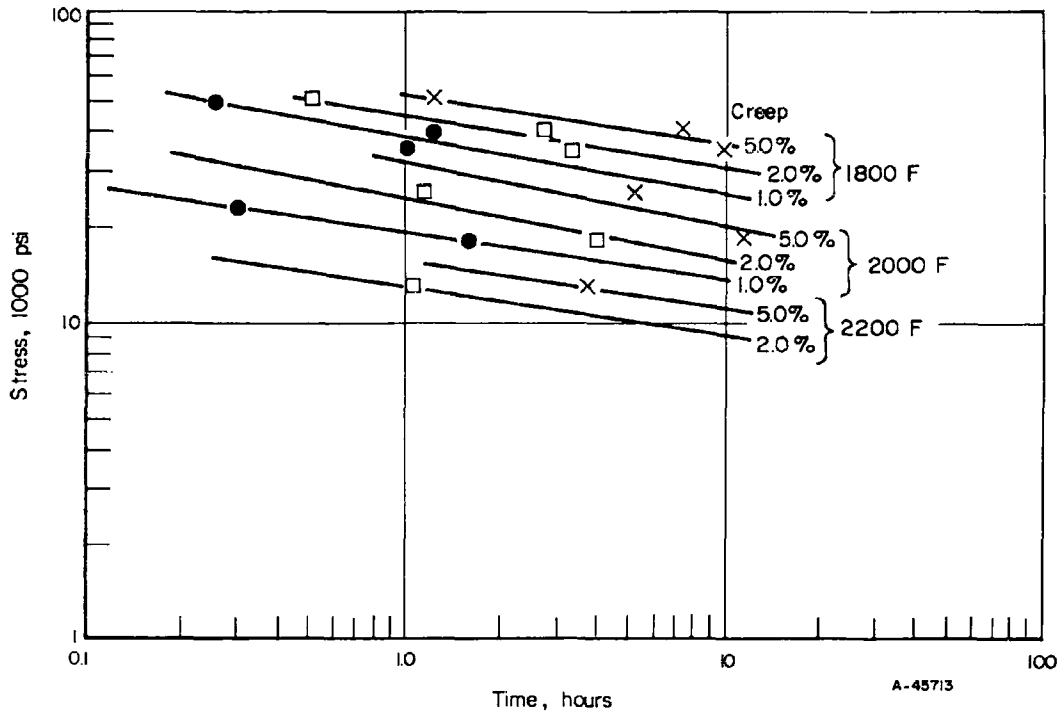


FIGURE A-49. CREEP DEFORMATION OF STRESS-RELIEVED FS-82 SHEET (0.040 INCH) AT 1800, 2000, AND 2200 F[4]

Stress relieved 1 hour at 1900 F.

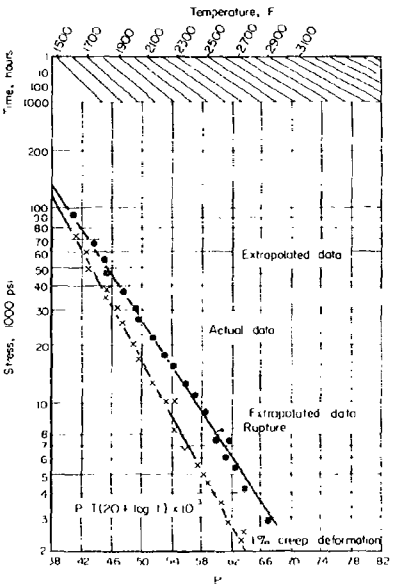


FIGURE A-50. CREEP DEFORMATION AND RUPTURE STRENGTHS OF STRESS-RELIEVED FS-82 SHEET (0.040 INCH)[4]

Stress relieved 1 hour at 1900 F.

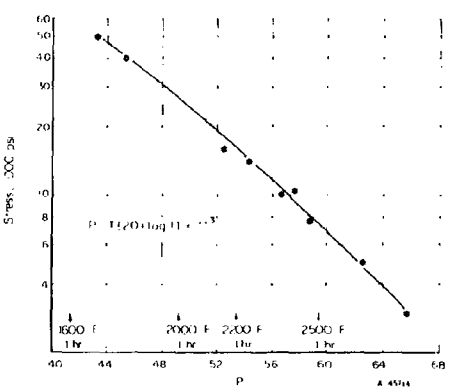


FIGURE A-51. STRESS-RUPTURE CHARACTERISTICS OF STRESS-RELIEVED FS-82 SHEET (0.125 INCH)[3]

Stress relieved 1 hour at 1900 F.

TABLE A-52. BEARING STRENGTH OF STRESS-RELIEVED FS-82 SHEET (0.120-INCH) FROM ROOM TEMPERATURE TO 2000 F[a][3]

Temperature,	Bearing Strength, 1000 psi	Bearing Strength/ Tensile Strength Ratio	Bearing Yield Strength, 1000 psi	Bearing Yield Strength/ Yield Strength Ratio
		Edge Distance 0.375 Inch (1.5d)		
RT	137.1	1.5	105.2	1.3
	139.2	1.5	103.0	1.2
1600	113.8	1.6	91.0	1.5
	110.5	1.6	99.2	1.7
2000	74.2	1.4	68.4	1.6
	71.5	1.4	68.9	1.6
		Edge Distance 0.500 Inch (2.0d)		
RT	185.0	2.0	109.8	1.3
	187.0	2.1	114.1	1.4
1600	140.7	2.0	106.8	1.8
2000	100.7	2.0	77.6	1.8
	99.5	1.9	72.9	1.7

(a) Stress relieved 1 hour at 1900 F.

4. Metallurgical Properties

a. Fabricability: can be fabricated using most conventional fabrication practices and procedures; readily cold workable[6]

b. Transition temperature: <-65 F for stress-relieved (1 hour at 1900 F) sheet (0.070 inch)[3]

c. Weldability: can readily be welded using TIG techniques; welded sheet material is ductile below room temperature

d. Stress-relief temperature: 1 hour at 1900 F for sheet material[3,4]

e. Recrystallization temperature: effect of annealing temperature on recrystallization and hardness of sheet material[3]

1-Hour Annealing Temperature, F	Recrystallization, per cent	Hardness, VHN
As received[a]	0	190
1800	0	182
2000	0	172
2100	50	119
2200	100	107
2400	100	118

(a) Stress relieved 1 hour at 1900 F.

References

(1) Moreen, H. A., "A Survey of the Properties of Commercial Columbium Alloys", Fansteel Metallurgical Corp., Internal Report (1963).

(2) Michael, A. B., and Gentry, W. O., "The Status of and Trend of Development of Molybdenum, Columbium, Tantalum, and Tungsten Alloys", Fansteel Metallurgical Corp., paper presented at The NATO AGARD Conference, Oslo, Norway (June 23-29, 1963).

(3) Neff, C. W., Frank, R. G., and Luft, L., "Refractory Metals Structural Development Program", Refractory Alloy and Coating Development, Volume II, McDonnell Aircraft Corp. and General Electric Co., ASD TR 61-392 (October, 1961).

(4) Jones, R. L., "The Elevated Temperature Tensile and Creep-Rupture Properties of the FS-82 Columbium Alloy", Convair (Astronautics) Division, General Dynamics Corp., Report ERR-AN-049 (April 17, 1961).

(5) Dana, A. W., et al., "Columbium and Columbium Alloy Extrusion Program", Metals Products, Pigments Department, E. I. du Pont de Nemours and Co., Inc., Contract No. AF 33(600)-40700, Interim Report 1 (June 30, 1960).

(6) "Refractory Alloy Foil Rolling Development Program", E. I. du Pont de Nemours and Co., Inc., Contract No. AF 33(657)-8912 (October, 1962).

Cb-10Ti-5Zr

1. Identification of Material

   a. Designation: D-36 (Du Pont)

   b. Chemical composition: Table A-53

   c. Forms available: sheet, strip, plate, bar, and tube hollows[1, 2]

TABLE A-53. CHEMICAL REQUIREMENTS FOR D-36 FABRICATED SHAPES[1]

Element	Content, Maximum, weight per cent (a)	(b)
Ti	9.0 min-11.0 max	9.0 min-11.0 max
Zr	4.0 min-6.0 max	4.0 min-6.0 max
O	0.0400	0.0300
H	0.0020	0.0020
N	0.0100	0.0100
C	0.0100	0.0100
Cb	By difference	By difference

(a) Sheet, strip, plate, rectangular bar, and round bar.
(b) Tube hollows.

2. Physical Properties

   a. Melting point: 3500 F[2]

   b. Density: 0.286 lb/in.^{3}[2]

   c. Thermal expansion: Figure A-52

   d. Thermal conductivity: Figure A-53

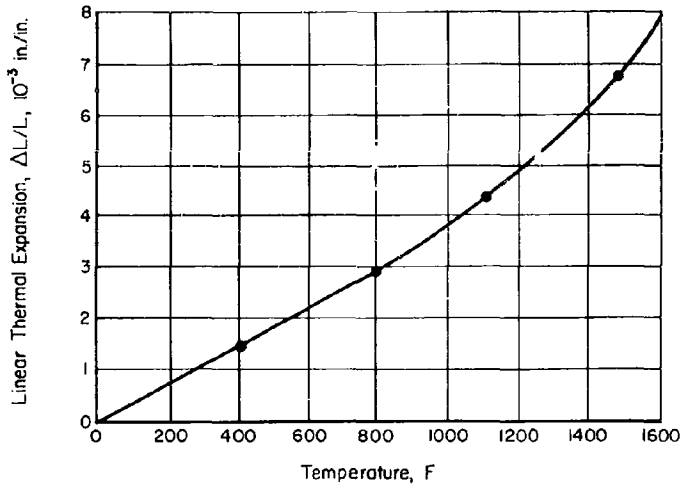


FIGURE A-52. THERMAL EXPANSION OF ARC-MELTED D-36[2]

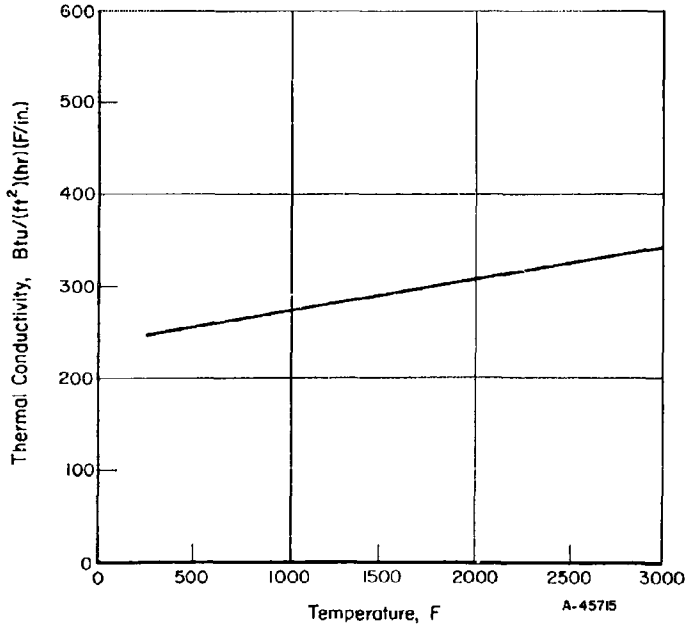


FIGURE A-53. THERMAL CONDUCTIVITY OF ARC-MELTED D-36[2]

3. Mechanical Properties

a. Tensile Properties at Room Temperature

Ultimate tensile strength: Tables A-54 and A-9-3

Tensile yield strength: Tables A-54 and A-55

Elongation: Tables A-54 and A-55

Reduction in area: Table A-54

Modulus of elasticity: 16.5×10^6 psi[2]

b. Effect of Temperature on Tensile Properties

Ultimate tensile strength: Figure A-54

Tensile yield strength: Figure A-54

Elongation: Figure A-54

c. Creep and Stress-Rupture Properties

Figure A-55

TABLE A-54. ROOM-TEMPERATURE TENSILE PROPERTIES FOR RECRYSTALLIZED D-36 FABRICATED SHAPES[a][1]

Comments	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent
		Sheet and Strip		
0.006 in. to 0.020 in., incl., min values	70	60	15 (2 in.)	--
Over 0.020 in. to 0.187 in., incl., min values	70	60	17 (2 in.)	--
		Plate and Rectangular Bar		
Typical average	74	67	20 (2 in. or 4D)	--
Probable minimum	65	58	15 (2 in. or 4D)	--
		Round Bar		
Minimum	65	58	20 (4D)	50

(a) Test rate 0.005 ± 0.002 inch per inch per minute through 0.6 per cent offset, then 0.05 ± 0.02 inch per inch per minute to failure. Typical analyses 9.0-11.0% Ti, 4.0-6.0% Zr, <0.0400% O, <0.0020% H, <0.0100% N, and <0.0100% C.

TABLE A-55. ROOM-TEMPERATURE TENSILE PROPERTIES OF D-36 REROLL STOCK AND FINISHED FOIL[a][3]

Coil Identification	Gage, inch	Recrystallization, per cent	ASTM Grain Size	Test Direction	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 2 Inches, per cent
			Reroll Foil Stock				
770	0.054	100	6.5	T	76.1	59.7	24.0
445	0.060	100	5.5	L	70.8	57.0	30.0
				T	71.5	59.1	30.0
658	0.053	100	6.5	T	77.6	64.5	27.0
413	0.054	100	6.0	T	77.8	62.8	29.2
348	0.052	100	5.5	L	76.5	65.0	29.2
				T	77.6	66.4	28.7
36-9	0.052	100	7.5	L	74.0	63.4	28.0
				T	74.7	63.4	27.0
36-10	0.051	100	5.5	L	74.7	63.1	21.0
				T	75.5	62.7	20.7
			Finished Foil				
444	0.010	90	8.5	L	80.6	73.2	19.5
				T	76.7	67.5	19.0
444(1)[b]	0.010	60	9.0	L	85.9	71.4	2.0
				T	87.1	77.3	2.5
445(2)[b]	0.010	35	9.5	L	86.1	74.9	9.2
				T	89.1	78.0	4.7
36-413	0.010	100	9.0	L	75.5	66.6	20.5
				T	79.3	70.2	22.7
766	0.006	90	9.0	L	78.1	75.0	23.0
				T	81.5	74.8	14.3
770	0.006	100	8.0	L	75.5	64.1	20.5
				T	77.4	68.8	20.5
36-9(S)[c]	0.006	100	8.5	L	71.2	59.2	27.0
				T	74.0	61.5	18.0
36-9	0.006	100	9.0	L	71.3	63.3	17.0
				T	73.2	63.6	19.0
36-10T1	0.006	100	8.5	L	76.7	68.9	20.0
				T	79.8	70.4	22.2
36-10T3(S)[c]	0.006	100	8.5	L	79.0	67.5	20.0
				T	83.7	67.5	21.7

TABLE A-55. (Continued)

Coil Identification	Gage, inch	Recrystallization, per cent	ASTM Grain Size	Test Direction	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 2 Inches, per cent
			Finished Foil (Continued)				
761	0.002	100	9.5	L	83.0	79.0	15.5
36-348	0.002	75	9.5	L	78.6	68.9	12.0
				T	71.1	67.0	13.5

(a) Test rate 0.005 inch per inch per minute to 0.2 per cent yield, then 0.05 inch per inch per minute to failure. Analyses are as follows:

Coil Identification	Gage, inch	Weight Per Cent Ti	Weight Per Cent Zr	PPM O	PPM N	PPM C	PPM H
			Reroll Foil Stock				
770	0.054	10.2	5.0	179	19	51	<10
445	0.060	10.2	4.7	173	21	63	<10
658	0.053	10.0	4.8	239	25	27	<10
413	0.054	9.8	5.2	179	30	42	<10
348	0.052	9.8	5.0	182	33	40	<10
36-9	0.052	10.4	4.7	105	63	25	<5
36-10	0.051	10.5	4.9	205	37	85	<5
			Finished Foil				
444	0.010	--	--	70	80	36	<10
444(1)	0.010	--	--	2200	80	84	<10
445(2)	0.010	--	--	950	73	42	11
36-413	0.010	--	--	105	14	40	<5
766	0.006	--	--	165	88	48	<10
770	0.006	--	--	80	67	130	<10
36-9(S)	0.006	--	--	205	25	100	<10
36-9	0.006	--	--	240	18	45	<10
36-10T1	0.006	--	--	340	27	70	<5
36-10T3(S)	0.006	--	--	315, 520	37	130, 395	<10
761	0.002	--	--	300	70	78	<10
36-348	0.002	--	--	660	43	365	<5

(b) Sample taken from area with discolored surface.
(c) Strand annealed.

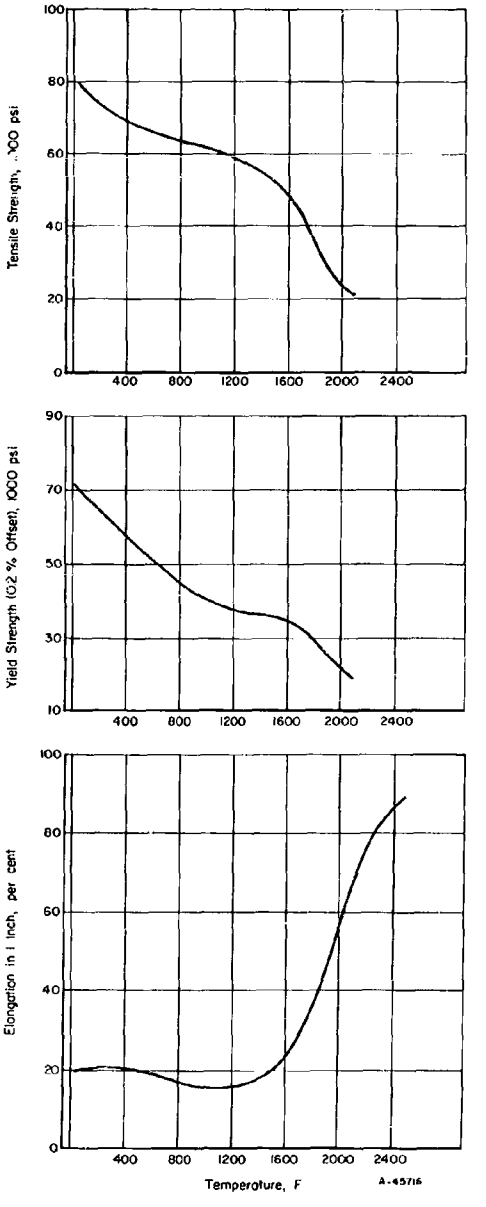


FIGURE A-54. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF ARC-MELTED RECRYSTALLIZED D-36 SHEET (0.040 INCH)[2]

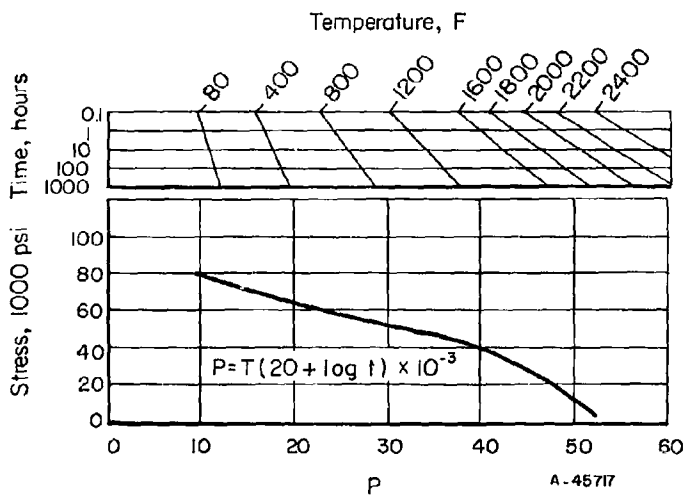


FIGURE A-55. STRESS-RUPTURE CHARACTERISTICS OF ARC-MELTED D-36 IN ARGON FROM ROOM-TEMPERATURE TO 2400 F[2]

4. Metallurgical Properties

   a. Fabricability: readily fabricated from arc-melted ingot using primary breakdown extrusion or forging and subsequent standard conversion to mill shapes[2]

   b. Transition temperature: <RT[1, 2]

   c. Weldability: fusion and resistance weldable by all standard processes including hand TIG welding; in the as-welded condition, fusion welds in sheet can be bent to greater than 2T, provided adequate protection from the atmosphere is maintained during welding[2]

References

(1) "Product Specification – Columbium Base Alloys", A Report From Du Pont, Pigments Department – Metal Products, E. I. du Pont de Nemours and Co., Inc.

(2) "Du Pont Metal Products· Columbium Product Data", E. I. du Pont de Nemours and Co., Inc., Sheet No. 3 (1963).

(3) Personal communication with G. P. Trost, Metals and Controls Inc., regarding "Development of Optimum Processing Parameters for Refractory Metal Foil", Contract No. AF 33(657)-9384 (June, 1963).

Cb-10Ti-10Mo-0.1C

1. Identification of Material

   a. Designation: D-31 (Du Pont)

   b. Chemical composition: Table A-56

   c. Forms available: sheet, strip, plate, bar, and tube hollows[1,2]

TABLE A-56. CHEMICAL REQUIREMENTS FOR D-31 FABRICATED SHAPES[1]

Element	Content, Maximum, weight per cent (a)	(b)
Ti	9.0 min - 11.0 max	9.0 min - 11.0 max
Mo	9.0 min - 11.0 max	9.0 min - 11.0 max
O	0.0250	0.0250
H	0.0020	0.0020
N	0.0070	0.0100
C	0.08 min - 0.12 max	0.08 min - 0.12 max
Cb	By difference	By difference

(a) Sheet, strip, and round bar.
(b) Plate and rectangular bar.

2. Physical Properties

   a. Melting point: 4100 F[2]

   b. Density: 0.292 lb/in.^{3}[2]

   c. Thermal expansion: linear coefficient is estimated to be 4.1×10^{-6}/F (0-1800 F)[3]

   d. Thermal conductivity: 500 Btu/(ft^2)(hr)(F/in) at 2200 F[3]

3. Mechanical Properties

   a. Tensile Properties at Room Temperature

      Ultimate tensile strength: Tables A-57 through A-60

      Tensile yield strength: Tables A-57 through A-60

      Elongation: Tables A-57 through A-60

      Reduction in area: Tables A-57 through A-60

      Modulus of elasticity: 16.5×10^6 psi[2]

   b. Effect of Temperature on Tensile Properties

      Ultimate tensile strength: Tables A-61 and A-62
      Figures A-56 through A-58

      Tensile yield strength: Tables A-61 and A-62
      Figure A-58

      Elongation: Tables A-61 and A-62
      Figure A-58

      Reduction in area: Tables A-61 and A-62

      Modulus of elasticity: Figure A-59

   c. Creep and Stress-Rupture Properties

      Tables A-63 and A-64
      Figures A-60 through A-63

   d. Other Selected Mechanical Properties

      Fatigue: Table A-65
      Figure A-64

TABLE A-57. ROOM-TEMPERATURE TENSILE PROPERTIES FOR STRESS-RELIEVED D-31 FABRICATED SHAPES[a][1]

Comments	Tensile Strength, 1000 psi	Yield Strength, (0.2% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent
	Sheet and Strip[b]			
0.006 in. to 0.020 in., incl., min values	85	80	8 (2 in)	--
Over 0.020 in. to 0.187 in., incl., min values	85	80	10 (2 in)	--
	Plate and Rectangular Bar[c]			
Minimum	75	65	10 (2 in or 4D)	--
	Round Bar[b]			
Minimum	75	65	10 (4D)	20

(a) Test rate 0.005 ± 0.002 inch per inch per minute through 0.6 per cent offset, then 0.05 ± 0.02 inch per inch per minute to failure.
(b) Typical analyses 9.0-11.0% Ti, 9.0-11.0% Mo, <0.0250% O, <0.0020% H, <0.0070% N, 0.08-0.12% C.
(c) Typical analyses 9.0-11.0% Ti, 9.0-11.0% Mo, <0.0250% O, <0.0020% H, <0.0100% N, 0.08-0.12% C.

TABLE A-58. ROOM-TEMPERATURE TENSILE PROPERTIES OF D-31 EXTRUSIONS

Condition	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent	Reduction in Area, per cent	Reference
As extruded (4:1)[a]	96	94	9	11	4
As extruded (8:1)	100	92	22	47	4
Extruded (8:1), 1 hr 2450 F[a]	92.5	--	--	--	4
Extruded, 1 hr 2500 F	100.7 (T)	87.4 (T)	17.2 (T)	21.3 (T)	5

(a) Test rate 0.05 inch per inch per minute.

TABLE A-59. ROOM-TEMPERATURE TENSILE PROPERTIES OF ANNEALED D-31 UPSET FORGINGS[a][5]

Forging Temperature, F	Upset Reduction, per cent	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent
2000	48	99.4	83.9	34	47
2200	49	100.3	85.6	34	47
2400	51	100.0	82.7	29	47
2000	73	99.0	85.8	35	52
2200	74	95.8	87.6	37	55
2400	73	98.7	83.7	38	50

(a) Annealed 1 hour at 2200 F.

TABLE A-60. EFFECT OF ANNEALING TEMPERATURE ON THE ROOM-TEMPERATURE TENSILE PROPERTIES OF D-31 COLD-ROLLED SHEET (0.060 INCH)[a][4]

1-Hour Annealing Temperature, F	Test Direction	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent	Structure
As rolled	L	125	122	5	Fibered
	T	132	128	5	Fibered
1750	L	105	100	15	Fibered
	T	105	105	10	Fibered
2150	L	99	89	--	100% rex.
	T	100	92	20	100% rex.
2300	L	98	90	--	100% rex.
	T	99	87	--	100% rex.
2450	L	90	--	--	100% rex.
	T	90	--	--	100% rex.

(a) Test rate 0.05 inch per inch per minute.

TABLE A-61. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF D-31 EXTRUSIONS[4]

Temperature, F	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent	Reduction in Area, per cent
		As Extruded (4:1)[a]		
RT	93	94	9	11
1800	37	35	40	72
2000	29	28	50	70
		As Extruded (8:1)[b]		
RT	100	92	22	47
800	67	54	22	75
1150	70.5	52	19	42
1500	63	49	6	12
1700	57	51	6	9
1900	40	38	13	13
2000	34.5	33	12	9
2200	25	22	14	13
2400	19.5	--	8	11
2600	11	--	--	40
		Extruded (8:1), Recrystallized 1 Hour at 2450 F[a]		
RT	92.5	--	--	--
200	91	86.8	5	7
400	79.9	71.3	23	71
600	67.7	55.2	28	76
800	67.1	55.2	23	82
1000	66	47.9	19	80
1200	60.2	46.0	7	6
1400	54.1	38.6	19	70
1600	45.9	36.1	9	16
1800	36.3	32.7	13	20
2000	26.2	25.8	25	23

(a) Test rate 0.05 inch per inch per minute.
(b) Tested in air.

TABLE A-62. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF UPSET FORGED AND ANNEALED D-31[2][5]

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent
1000	54.4	--	14	78
2000	29.2	25.3	36	74
2300	17.5	--	86	82
2600	10.2	8.0	100	65

(a) Forged 75 per cent at 2200 F, annealed 1 hour at 2200 F.

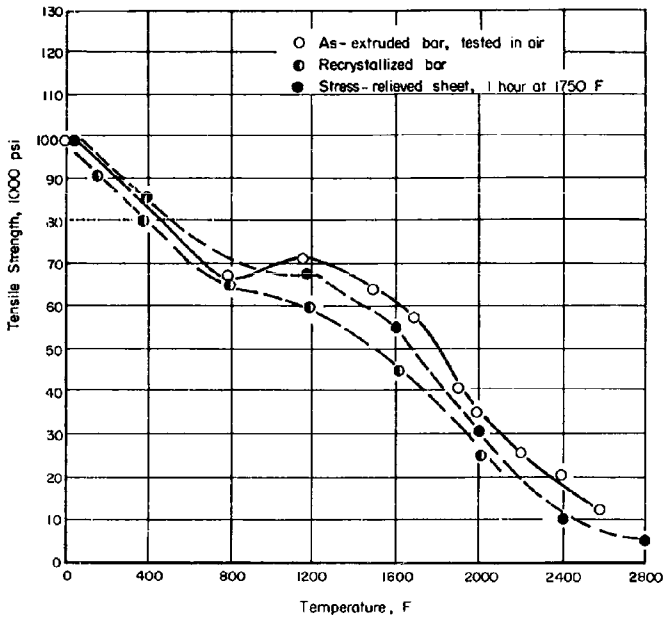


FIGURE A-56. EFFECT OF TEMPERATURE ON THE TENSILE STRENGTH OF D-31[3]

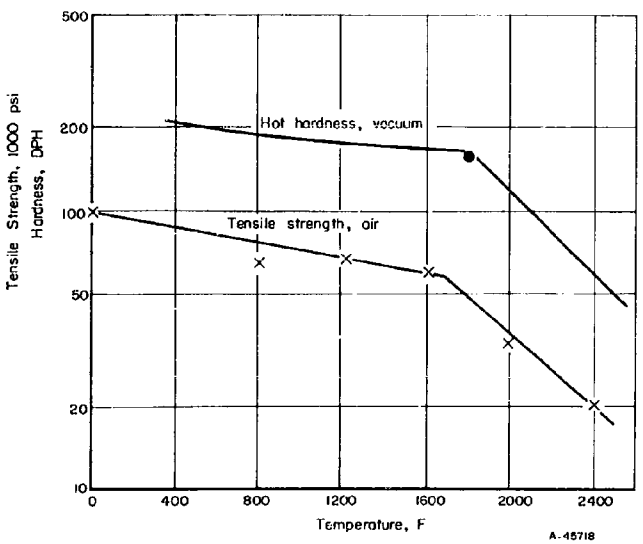


FIGURE A-57. EFFECT OF TEMPERATURE ON THE TENSILE STRENGTH AND HOT HARDNESS OF EXTRUDED D-31 BAR[3]

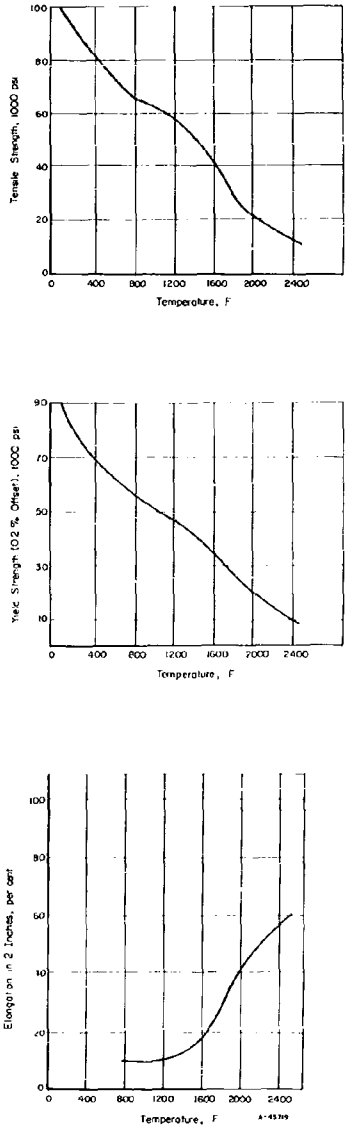


FIGURE A-58. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF ARC-MELTED RECRYSTALLIZED D-31 SHEET (0.040 INCH)(2)

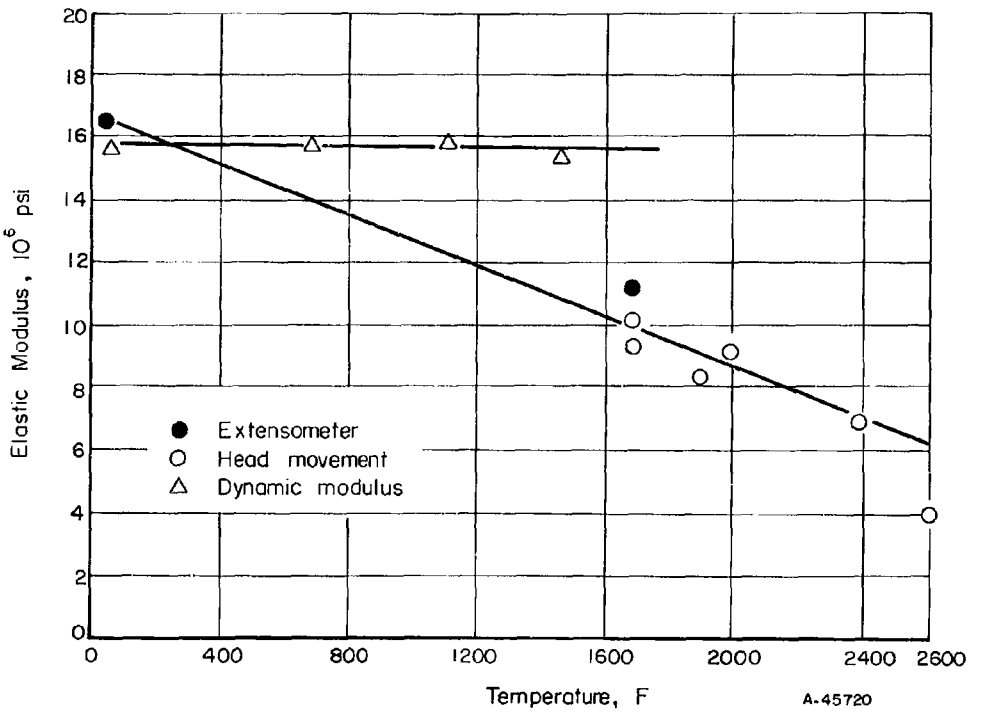


FIGURE A-59. EFFECT OF TEMPERATURE ON THE MODULUS OF ELASTICITY OF D-31 TESTED IN AIR[5]

TABLE A-63. STRESS-RUPTURE PROPERTIES OF UPSET FORGED AND ANNEALED D-31[a][5]

Temperature, F	Stress, 1000 psi	Rupture Life, Hours	Elongation in 1/2 Inch, per cent	Reduction in Area, per cent
2000	22	0.2	76	62
	18	0.5	76	92
	11	17.8	82	81
2300	15	0.05	24	79
	10	0.8	112	72
	8	6.0	51	90
2600	9	0.1	108	79
	5	2.3	124	73
	3.5	10.2	85	65

(a) Forged 75 per cent at 2200 F, annealed 1 hour at 2200 F.

TABLE A-64. SHORT-TIME CREEP AND STRESS-RUPTURE BEHAVIOR OF D-31 SHEET (0.042 INCH)[6]

Temperature, F	Stress, 1000 psi	Time to Produce Indicated Creep, seconds					Rupture Time, seconds
		0.5%	1.0%	2.0%	5.0%	10.0%	
1900	25.0	1	2.5	5.4	14.5	28	80
	20.0	5.8	14	30	73	140	400
	15.0	32	80	160	360	740	1950
2100	15.0	6	10	19	38	72	150

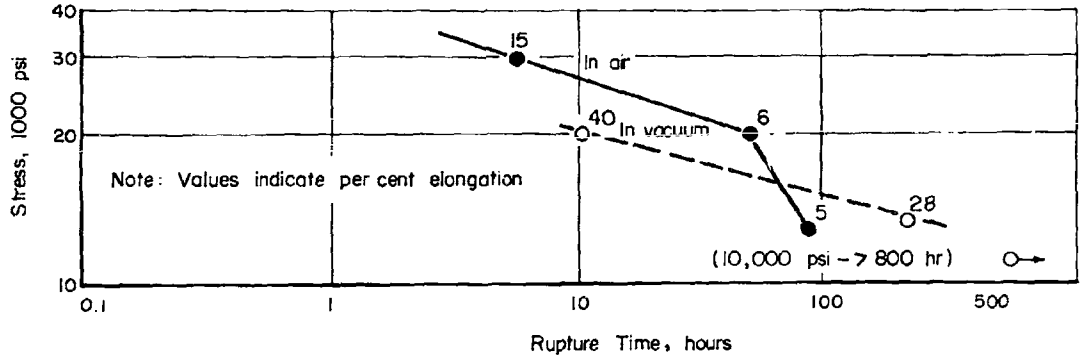


FIGURE A-60. STRESS-RUPTURE DATA FOR D-31 TESTED IN AIR AND VACUUM AT 1800 F[3]

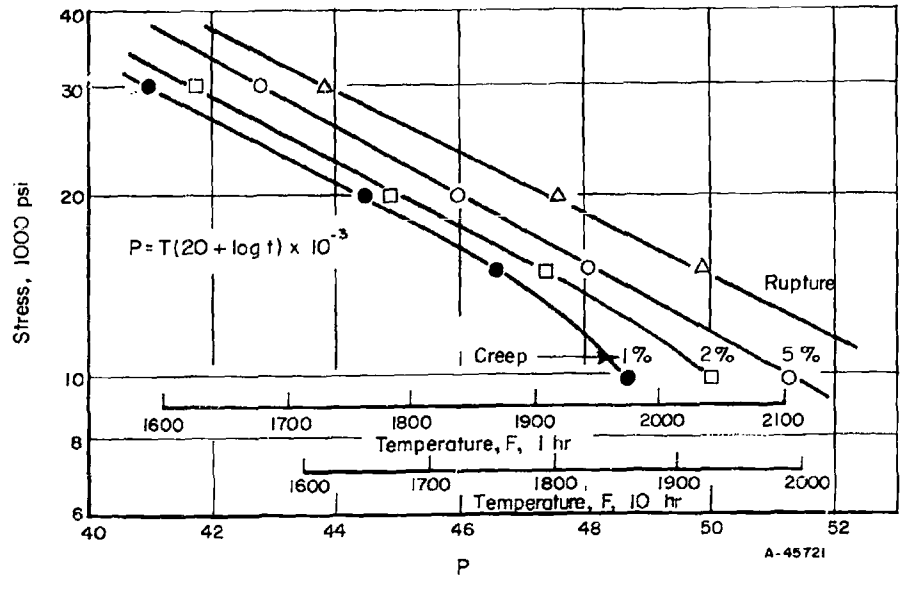


FIGURE A-61. CREEP AND STRESS-RUPTURE BEHAVIOR OF STRESS-RELIEVED D-31 SHEET (0.060 INCH)[3]

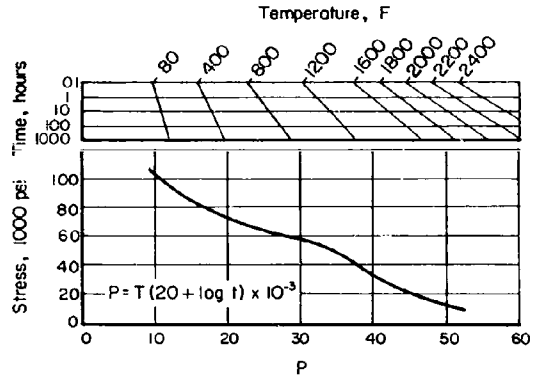


FIGURE A-62. STRESS-RUPTURE CHARACTERISTICS OF ARC-MELTED D-31 IN ARGON FROM ROOM TEMPERATURE TO 2400 F(2)

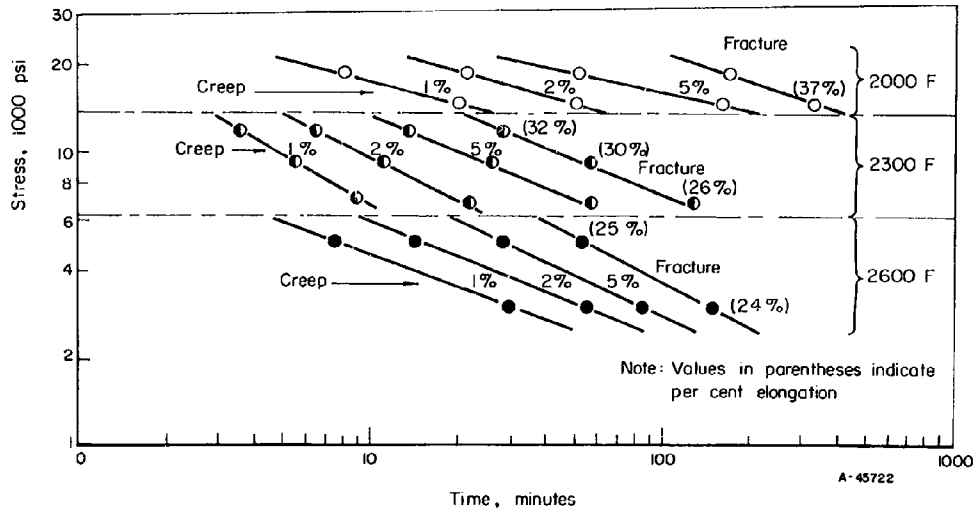


FIGURE A-63. CREEP AND STRESS-RUPTURE BEHAVIOR OF D-31 TESTED IN AIR(3)

TABLE A-65. TENSION-TENSION FATIGUE DATA FOR D-31 SHEET (0.042 INCH)[6]

RT		2300 F	
Maximum Stress, 1000 psi	Cycles to Failure	Maximum Stress, 1000 psi	Cycles to Failure
50	> 50 x 10^5	12.2	4.3 x 10^5
53	24 x 10^5	12.3	6.0 x 10^5
55	13 x 10^5	14.7	49 x 10^4
60	40 x 10^4	14.7	72 x 10^4
65	37 x 10^4	18.6	7.0 x 10^3
75	11 x 10^4	18.6	6.5 x 10^3
75	12 x 10^4	--	--
90	17 x 10^3	--	--
90	18 x 10^3	--	--

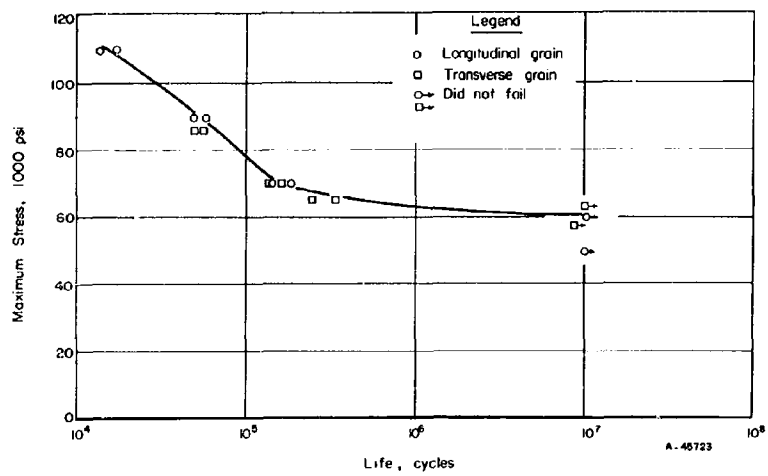


FIGURE A-64. COMPLETELY REVERSED SHEET-BENDING FATIGUE PROPERTIES OF STRESS-RELIEVED D-31 SHEET (0.020 INCH) AT ROOM TEMPERATURE[7]

4. Metallurgical Properties

a. Fabricability: readily fabricated from arc-melted ingot using primary breakdown extrusion or forging and subsequent standard conversion to mill shapes[2]

b. Transition temperature: <RT[1,2]

c. Weldability: cannot be fusion welded by standard arc processes; can be welded using high-speed electron-beam or resistance techniques[2]

d. Recrystallization temperature: effect of annealing temperature on recrystallization and hardness of extrusions[5]

Temperature, F	Recrystallization, per cent	Hardness, VHN
As extruded	0	249
2200	40	221
2300	60	222
2400	100	227
2500	100	230
2600	100	231
2700	100	258

Figure A-65

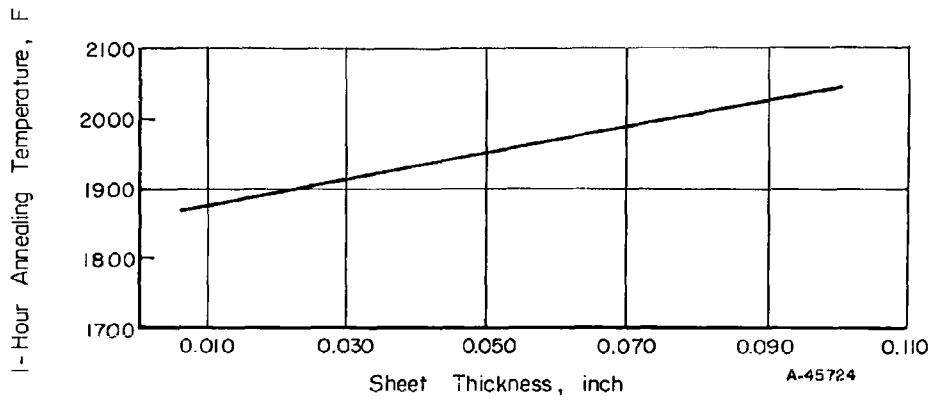


FIGURE A-65. TEMPERATURE FOR COMPLETE RECRYSTALLIZATION OF D-31 SHEET[3]

References

(1) "Product Specification – Columbium Base Alloys", A report from Du Point, Pigments Department – Metal Products, E. I. du Pont de Nemours and Co., Inc.

(2) "Du Point Metal Products • Columbium Product Data", E. I. du Pont de Nemours and Co., Inc., Sheet No. 3 (1963).

(3) "Technical Bulletin, Du Pont Columbium Alloy D-31", E. I. du Pont de Nemours & Co., Inc. Pigments Department/Thompson Ramo Wooldridge, Tapco Group (April 1960).

(4) Dana, A. W., et al., "Columbium and Columbium Alloy Extrusion Program", E. I. du Pont de Nemours and Co., Inc., Contract No. AF 33(600)-40700, Interim Report 1 (June 30, 1960).

(5) Carson, R. O., "The Development of Optimum Manufacturing Methods for Columbium Alloy Forgings", Crucible Steel Co. of America, Contract No. AF 33(600)-39944, ASD Interim Report 7-782 (V) (August, 1961).

(6) Churchill, R. L., "Compilation of Unpublished Materials Information", General Dynamics Corp., Contract No. AF 33(657)-7248, FPR-003, Issue No. 2, TR 30-1939, p 15-18 (November 15, 1962).

(7) Foster, L. R., and Stein, B. A., "Tensile Properties and Sheet-Bending Fatigue Properties of Some Refractory Metals at Room Temperature", National Aeronautics and Space Administration, NASA TN D-1592 (January, 1963).

Cb-5W-1Zr

1. Identification of Material

   a. Designation: AS-55 (General Electric)

   b. Chemical composition: nominal analyses[1]

Element	Weight Per Cent
W	5-10
Zr	0.8-1.2
Y	0.2-1.0[a]
C	0.04-0.08
O	0.10 max.[a]
N	0.03
Cb	Balance

(a) Starting material content. Oxygen and yttrium analyses of arc-melted ingot will be lower.

   c. Forms available: ingot and fabricated shapes on a best efforts basis

2. Physical Properties

   a. Density: 0.317 lb/in.^{3} (calculated)

3. Mechanical Properties

   a. Tensile Properties at Room Temperature

      Ultimate tensile strength: Table A-66

      Tensile yield strength: Table A-66

      Elongation: Table A-66

   b. Effect of Temperature on Tensile Properties

      Ultimate tensile strength: Table A-67

      Tensile yield strength: Table A-67

      Elongation: Table A-67

   c. Creep and Stress-Rupture Properties

Figure A-66

d. Other Selected Mechanical Properties

Bend ductility: ductility of sheet (0.040 inch) as affected by aging at various temperatures and times[1]

Aging Conditions			Ductility	
Temperature, F	Time, Hours	Aging Environment	Cold Rolled	Annealed 1 Hr, 2200 F
Unaged	--	--	<1T	<1T
1700	20	Vacuum	<1T	<1T
1850	100	Potassium	<1T	--
1850	1000	Potassium	<1T	<1T
1850	1000	Vacuum	--	<1T

TABLE A-66. ROOM-TEMPERATURE TENSILE PROPERTIES OF AS-55 BAR AND SHEET[a][1]

Condition	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent
Stress-relieved bar (warm swaged, 1 hr 1800 F, 181 VHN)	84.7	65.4	22
Recrystallized sheet (cold rolled, 1 hr 2600 F, 135 VHN)	67.8	55.3	28

(a) Analyses 4.65% W, 1.0% Zr, 0.15% Y, 0.052% C, 0.022% O, and 0.028% N.

TABLE A-67. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF AS-55 BAR AND SHEET[a][1]

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent
Stress-Relieved Bar, Warm Swaged, 1 Hour at 1800 F, 181 VHN			
RT	84.7	65.4	22
1600	58.0	50.0	12
2000	40.0	38.3	15
2200	30.3	28.0	24
2500	14.1	12.4	44
Recrystallized Sheet, Cold Rolled, 1 Hour at 2600 F, 135 VHN			
RT	67.8	55.3	28
1600	41.1	23.3	22
2000	37.0	18.2	24
2200	~24.9	~16	~50

(a) Analyses 4.65% W, 1.0% Zr, 0.15% Y, 0.052% C, 0.022% O, and 0.028% N.

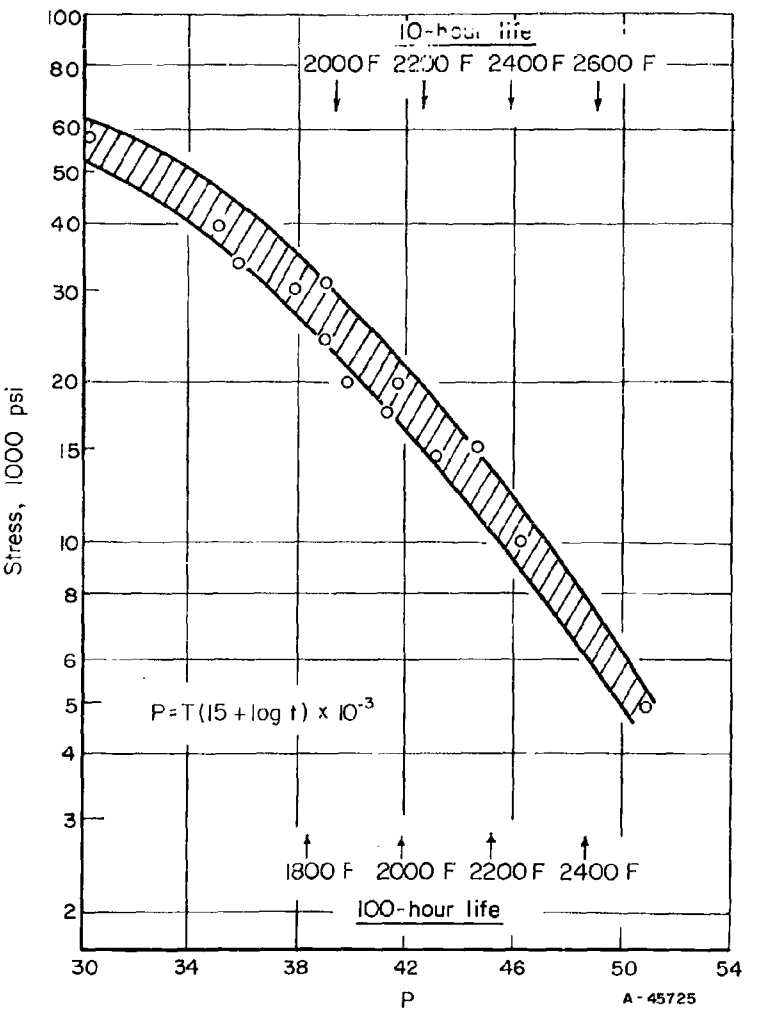


FIGURE A-66. STRESS-RUPTURE PROPERTIES OF AS-55(1)

Analyses 4.65% W, 1.0% Zr, 0.15% Y, 0.052% C, 0.022% O, and 0.028% N.

4. Metallurgical Properties

a. Fabricability: amenable to breakdown by forging as well as extrusion; temperatures in the region of 2000 to 2500 F are used, and large reductions can be made between anneals; following breakdown, billets can be converted to other wrought forms with relative ease; cold or warm rolling of thin sheet has been accomplished without difficulty[1]

b. Transition temperature: <RT[1]

c. Weldability: weldments produced by the TIG process are quite ductile in the as-welded condition; however, the low-temperature ductility of such welds is adversely affected by exposure to temperatures in the range 1600 to 1800 F[1]

d. Stress-relief temperature: 1 hour at 1800 F for warm-swaged bar[1]

e. Recrystallization temperature: 1 hour at 2600 F for cold-rolled sheet[1]

Reference

(1) "Recent General Electric Company Developments in Columbium-Base Alloys", Materials and Processes, Applied Research Operation, Flight Propulsion Laboratory Department, General Electric Co. (February, 1962).

Cb-10W-1Zr-0.1C

1. Identification of Material

   a. Designation: X-110, D-43 (Du Pont)

   b. Chemical composition: Table A-68

   c. Forms available: ingot and fabricated shapes on a best efforts basis

TABLE A-68. CHEMICAL COMPOSITION OF EXTRUDED D-43 BAR AND SHEET[1]

Form	Sample Location	Amount Present					
		Weight Per Cent		PPM			
		W	Zr	C	O	H	N
Extruded bar, 283	Front	8.2	1.4	725	22	6	37
	1/3 back	10.5	0.9	830	46	4	36
	2/3 back	10.3	0.93	885	44	10	37
	Back	10.2	0.97	855	52	9	45
Extruded bar, 284	Front	8.4	1.3	1140	19	5	38
	1/3 back	10.0	0.92	1175	40	6	33
	2/3 back	10.2	0.94	860	41	4	35
	Back	10.1	0.94	1045	46	4	33
Sheet, 0.063 inch	--	10.0	0.95	950	64	1	38
Sheet, 0.040 inch	--	9.8	0.94	920	50	3	33
Sheet, 0.020 inch	--	10.8	0.97	1005	60	1	32

2. Physical Properties

   a. Melting point: 4700 F (approximate)[2]

   b. Density: 0.326 lb/in.^{3}[2]

3. Mechanical Properties

   a. Tensile Properties at Room Temperature

      Ultimate tensile strength: Tables A-69 through A-71

      Tensile yield strength: Tables A-69 through A-71

      Elongation: Tables A-69 through A-71

      Reduction in area: Table A-69

   b. Effect of Temperature on Tensile Properties

      Ultimate tensile strength: Tables A-72 and A-73

      Tensile yield strength: Tables A-72 and A-73

      Elongation: Tables A-72 and A-73

   c. Creep and Stress-Rupture Properties

      Figure A-67

   d. Other Selected Mechanical Properties

      Bend ductility: 1T bend radius at room temperature for sheet (0.040 inch) material[2]

TABLE A-69. ROOM-TEMPERATURE TENSILE PROPERTIES OF D-43 EXTRUDED TUBE BLANKS[a][3]

Condition	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 4D, per cent	Reduction in Area, per cent
As extruded	94.0	78.0	18	67
	93.2	76.8	17	56
Annealed 1 hr 2200 F	96.0	69.9	21	63
	96.7	70.1	28	65
Annealed 2 hr 2600 F	78.5	59.1	24	62
	80.1	59.5	31	64

(a) Test rate 0.005 inch per inch per minute to yield, and 0.05 inch per inch per minute to failure.

TABLE A-70. ROOM-TEMPERATURE TENSILE PROPERTIES OF STRESS-RELIEVED D-43 SHEET (0.040 INCH)[a][2, 4]

Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1 Inch, per cent
95-100	75-80	14-18

(a) Stress relieved 1 hour at 2200 F. Test rate 0.05 inch per inch per minute. Typical analyses 10.2% W, 0.97% Zr, 0.08% C, 0.0125% O, and 0.040% N.

TABLE A-71. ROOM-TEMPERATURE TENSILE PROPERTIES OF STRESS-RELIEVED D-43 SHEET[a][1]

Thickness, inch	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent
0.020	82.0	66.3	12.5
	78.7	69.2	12.5
0.040	84.1	75.2	12.2
	85.4	75.7	12.4
0.063	84.1	75.6	14.5
	84.0	75.9	13.5

(a) Stress relieved at 2200 F. Test rate 0.005 inch per inch per minute to yield, then 0.05 inch per inch per minute to failure. Analyses are given below:

Thickness, inch	Weight Per Cent		PPM			
	W	Zr	C	O	H	N
0.020	10.8	0.97	1005	60	1	32
0.040	9.8	0.94	920	50	3	33
0.063	10.0	0.95	950	64	1	38

TABLE A-72. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF STRESS-RELIEVED D-43 SHEET (0.040 INCH)[a][2, 4]

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1 Inch, per cent
RT	95-100	75-80	14-18
2000	46-48	39-40	14-18
2200	34-37	23-27	14-20
2400	24-27	20-24	25-30
2600	12-15.5	12-14	27-35

(a) Stress relieved 1 hour at 2200 F. Test rate 0.05 inch per inch per minute. Typical analyses 10.2% W, 0.97% Zr, 0.08% C, 0.0125% O, and 0.040% N.

TABLE A-73. TENSILE PROPERTIES OF STRESS-RELIEVED D-43 SHEET AT 2200 F[a][1]

Thickness, inch	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent
0.020	30.5	27.8	12
	30.0	26.9	8
0.040	37.0	34.2	16
	37.0	34.8	12
0.063	37.0	34.1	16
	36.8	33.6	13

(a) Stress relieved at 2200 F. Test rate 0.005 inch per inch per minute to yield, then 0.05 inch per inch per minute to failure. Analyses are given below:

Thickness, inch	Weight Per Cent		PPM			
	W	Zr	C	O	H	N
0.020	10.8	0.97	1005	60	1	32
0.040	9.8	0.94	220	50	3	33
0.063	10.0	0.95	950	64	1	38

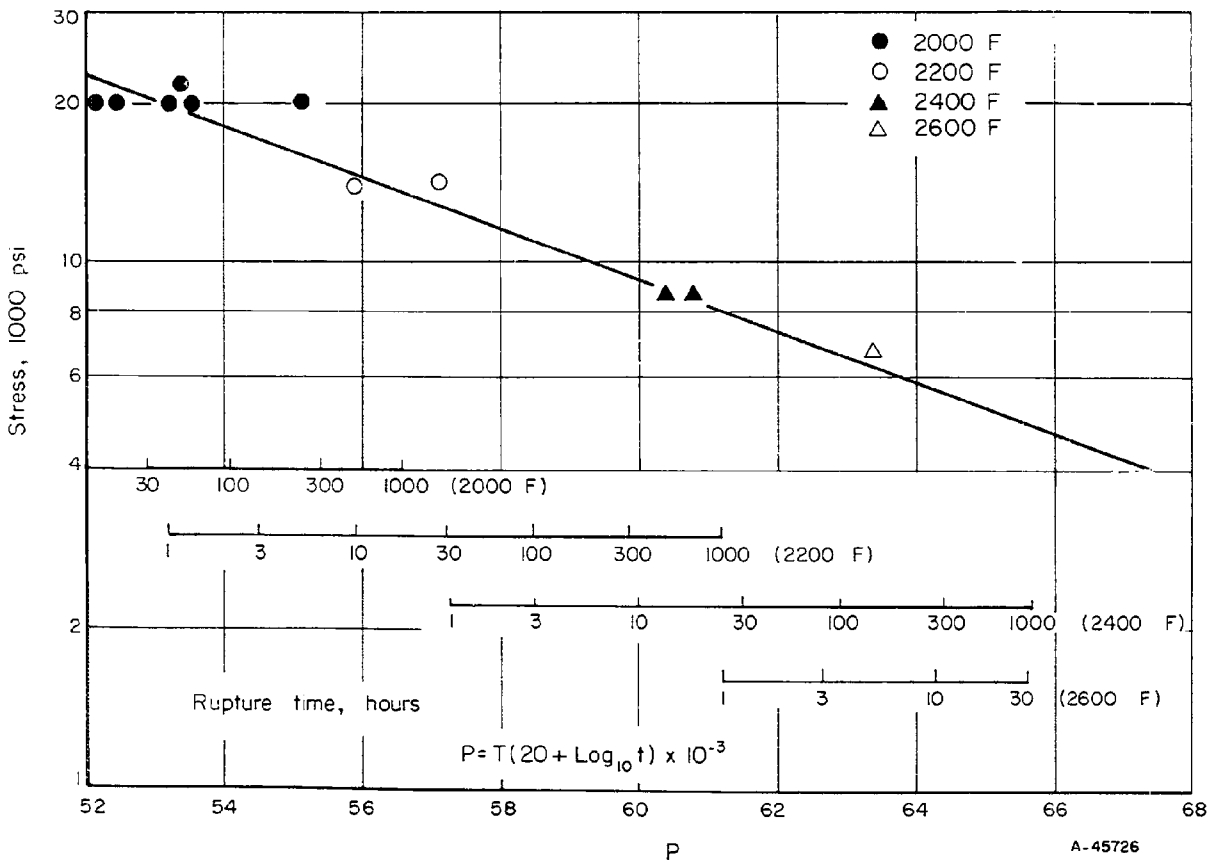


FIGURE A-67. RUPTURE CHARACTERISTICS OF D-43 AT 2000 TO 2600 F[4]

4. Metallurgical Properties

a. Fabricability: after high-temperature breakdown using conventional practices, final working operations are readily conducted at room temperature[4]

b. Transition temperature: <-100 F based on bend-test results[2]

c. Weldability: sheet material is ductile as welded; transverse weld bend tests can be bent over a 2T radius, >90 degrees, without cracking[2]

d. Stress-relief temperature: 1 hour at 2200 F for sheet material[1, 4]

e. Recrystallization temperature: 1 hour at 2400 F for sheet material[2]

References

(1) Mincher, A. L., "The Development of Optimum Manufacturing Methods for Columbium Alloy Sheet", Subcontract For The Development of Sheet Process For X-110 alloy, E. I. du Pont de Nemours and Co., Inc., Contract No. AF 33(600)-39942 (January, 1963).

(2) "Preliminary Data – Alloy X-110, Fabricable Columbium Alloy", E. I. du Pont de Nemours and Co., Inc. (January 9, 1963).

(3) Clark, J. S., "Columbium Alloy Extrusion Program", E. I. du Pont de Nemours and Co., Inc., Contract No. AF 33(600)-40700, Phase V: Tubing Program, Interim Report VII (February, 1963).

(4) "Refractory Alloy Foil Rolling Development Program", E. I. du Pont de Nemours and Co., Inc., Contract No. AF 33(657)-8912, Interim Report No. 1 (October, 1962).

Cb-10W-2.5Zr

1. Identification of Material

   a. Designation: Cb-752 (formerly Cb-74, Haynes Stellite)

   b. Chemical composition: Table A-74

   c. Forms available: ingot and most mill products

TABLE A-74. SELECTED CHEMICAL ANALYSES OF Cb-752

	Amount Present, weight per cent											
	Nominal.	Ingot						Sheet				
Element	Ref. (1)	Ref. (2)	Ref. (2)	Ref. (2)	Ref. (3)	Ref. (3)	Ref. (3)	Ref. (2)	Ref. (2)	Ref. (2)	Ref. (4)	Ref. (4)
W	10.0	8.48	9.40	10.49	10.06	10.49	10.20	--	--	--	9.45	10.04
Zr	2.5	1.90	2.45	2.54	2.45	2.54	2.46	--	--	--	2.45	3.23
C	0.0040	0.0200	0.0100	0.0030	0.004	0.003	0.002	--	--	--	0.01	0.027
O	0.0060	0.0290	0.0270	0.0040	0.005	0.004	0.010	0.0141	0.0179	0.0133	0.027	0.047
H	0.0006	0.0031	0.0024	0.0007	0.0006	0.0007	0.0006	0.0003	0.0007	0.0004	0.0024	0.0043
N	<0.0100	0.0050	0.0040	0.0100	<0.010	<0.010	<0.010	0.0084	0.0029	0.0057	0.004	0.004

2. Physical Properties

   a. Density: 0.326 lb/in.^{3}

   b. Thermal expansion: Table A-75

   c. Thermal conductivity: Table A-76

TABLE A-75. LINEAR COEFFICIENT OF THERMAL EXPANSION OF Cb-752[3]

Temperature Range, F	Mean Linear Thermal Expansion Coefficient, 10^{-6}/F Over Temperature Ranges Shown
68-200	3.8
68-400	3.9
68-600	3.9
68-800	4.0
68-1000	4.0
68-1200	4.1
68-1400	4.1
68-1600	4.2
68-1800	4.3
68-2000	4.4
68-2200	4.5

TABLE A-76. THERMAL CONDUCTIVITY OF Cb-752 FROM 500 TO 2400 F[3]

Temperature, F	Thermal Conductivity, Btu/(ft^2)(hr)(F/ft)
500	22.0
600	23.0
700	23.8
800	24.5
900	25.2
1000	25.8
1100	26.4
1200	26.8
1300	27.2
1400	27.6
1500	28.0
1600	28.3
1700	28.5
1800	28.6
1900	28.7
2000	28.8
2100	28.9
2200	29.0
2300	29.1
2400	29.2

3. Mechanical Properties

a. Tensile Properties at Room Temperature

Ultimate tensile strength: Tables A-77 through A-82

Tensile yield strength: Tables A-77 through A-82

Elongation: Tables A-77 through A-82

Reduction in area: Tables A-77 and A-78

Modulus of elasticity: 15.03×10^6 psi[3]

b. Effect of Temperature on Tensile Properties

Ultimate tensile strength: Tables A-83 through A-89
Figure A-68

Tensile yield strength: Tables A-84 through A-89
Figure A-68

Elongation: Tables A-83 through A-89
Figure A-68

Reduction in area: Table A-83

Modulus of elasticity: Table A-90

c. Notched Tensile Properties

Table A-91

d. Creep and Stress-Rupture Properties

Tables A-92 through A-94
Figure A-69

e. Other Selected Mechanical Properties

Impact: Table A-95

Bend ductility: both longitudinal and transverse recrystallized (1 hour at 2200 and 2800 F) sheet (0.035 and 0.010 inch) specimens exhibited a 1 to 3T bend radius at room temperature[2]

Shear strength: Table A-96

Bearing strength: Table A-97

TABLE A-77. ROOM-TEMPERATURE TENSILE PROPERTIES OF ANNEALED Cb-74 UPSET FORGINGS[a][5]

Forging Temperature, F	Upset Reduction, per cent	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent
2200	48	100.6	82.8	9	7
2400	47	102.6	84.0	13	9
2600	47	100.6	88.9	6	5
2200	71	101.9	85.3	35	34
2400	73	103.3	87.1	25	14
2600	71	102.5	86.7	13	8

(a) Annealed 1 hour at 2400 F, nominal composition Cb-10W-5Zr.

TABLE A-78. ROOM-TEMPERATURE TENSILE PROPERTIES OF Cb-752 BAR (0.250-INCH DIAMETER)[a][3]

Tensile Strength, 1000 psi	Yield Strength, (0.2% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent
85.9	68.6	31	70
89.1	70.6	26	30
87.5	68.9	33	69
85.1	65.8	31	63
88.9	68.9	30	64
86.9	68.3	32	70

(a) Test rate 0.005 inch per inch per minute to yield, then 0.05 inch per inch per minute to failure. Analyses 10.2% W, 2.7% Zr, 0.007% C, 0.015% O, 0.0006% H, and 0.004% N.

TABLE A-79. EFFECT OF SHEET THICKNESS ON THE ROOM-TEMPERATURE TENSILE PROPERTIES OF Cb-752[a][3]

Gage, inch	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 1 Inch, per cent
.012	78.0	59.3	23
.018	73.3	53.8	27
.018	80.8	62.8	27
.030	80.8	63.0	26

(a) Average data for three tests.

TABLE A-80. ROOM-TEMPERATURE TENSILE PROPERTIES OF Cb-752 SHEET[a][3]

Heat	Gage, inch	Direction	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1 Inch, per cent
7	.012	L	76.0	59.0	20
7	.012	T	74.0	57.4	16
7	.018	T	77.8	61.4	22
8	.012	L	79.1	65.9	15
8	.018	T	87.4	69.7	23
8	.030	L	85.2	70.5	20
17	.012	T	78.5	58.5	19
17	.018	L	76.6	58.4	25
17	.018	T	79.5	59.0	21
17	.030	L	83.6	70.0	24
17	.030	T	87.8	68.9	17

(a) Average data for three tests. Test rate 0.005 inch per inch per minute to yield, then 0.05 inch per inch per minute to fracture.

Heat	Ingot Composition, weight per cent					
	Al	Zr	C	O	H	N
7	10.06	2.45	0.004	0.005	0.0006	<0.010
8	10.49	2.54	0.003	0.004	0.0007	<0.010
17	10.20	2.46	0.002	0.010	0.0006	<0.010

TABLE A-81. EFFECT OF ANNEALING ON THE ROOM-TEMPERATURE TENSILE PROPERTIES OF Cb-752 SHEET (0.030 INCH)

1-Hour Annealing Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1 Inch, per cent
	Heat 10[a, b](4)		
2200[c]	85.7 (L)	70.2 (L)	21 (L)
	89.6 (T)	71.3 (T)	23 (T)
2300[d]	84.0	68.3	26
	Heat 11[a, e](4)		
2200[c]	87.4	75.0	15
2300[f]	80.2	65.4	22
	Heat 29[g](3)		
1900	96.4	87.8	13
2000	91.1	81.0	16
2100	81.4	67.8	21
2200	81.3	64.6	25

(a) Test rate 0.005 inch per inch per minute to yield, then 0.02 inch per inch per minute to failure.
(b) Analyses 9.45% W, 2.45% Zr, 0.01% C, 0.027% O, 0.0024% H, and 0.004% N.
(c) Average data from two tests.
(d) Average data from eight tests.
(e) Analyses 10.04% W, 3.23% Zr, 0.027% C, 0.047% O, 0.0043% H, and 0.004% N.
(f) Average data from ten tests.
(g) Average data from four tests. Test rate 0.005 inch per inch per minute to yield, then 0.05 inch per inch per minute to failure.

TABLE A-82. ROOM-TEMPERATURE TENSILE PROPERTIES OF Cb-752 REROLL STOCK AND FINISHED FOIL[a][6]

Coil Identification	Gage, inch	Recrystallization, per cent	ASTM Grain Size	Test Direction	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 2 Inches, per cent
			Reroll Foil Stock				
752-1, -2	0.031	50	9.5	L	84.6	69.3	22.9
				T	86.7	65.7	21.0
			Finished Foil				
752-1	0.006	90	10.0	L	85.5	68.1	22.0
				T	88.6	69.0	21.0
752-2	0.002	100	9.5	L	98.6	79.1	13.5
				T	113.3	91.1	8.4

(a) Test rate 0.005 inch per inch per minute to 0.2 per cent yield, then 0.05 inch per inch per minute to failure. Analyses are as follows:

Coil Identification	Gage, inch	Weight Per Cent W	Weight Per Cent Zr	PPM O	PPM N	PPM C	PPM H
			Reroll Foil Stock				
752-1, -2	0.031	9.95	2.55	75	138	40	<10
			Finished Foil				
752-1	0.006	--	--	115	112	45	<5
752-2	0.002	--	--	140	162	60	<10

TABLE A-83. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF UPSET FORGED AND ANNEALED Cb-74[a][5]

Temperature, F	Tensile Strength, 1000 psi	Elongation, per cent	Reduction in Area, per cent
1000	70.4	30	86
2000	52.0	53	88
2300	34.4	86	99
2600	24.5	118	99

(a) Forged 75 per cent at 2200 F, annealed 1 hour at 2400 F. Nominal composition Cb-10W-5Zr.

TABLE A-34. EFFECT OF TEMPERATURE AND THE TENSILE PROPERTIES OF Cb-752 BAR (0.250-INCH DIAMETER)[a][3]

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent
RT[b]	87.2	68.5	31
750	58.4	39.8	30
	59.5	41.7	38
	62.3	39.5	32
1000	52.5	36.2	28
	55.6	36.3	30
	55.6	36.9	29
2000	39.1	28.5	29
	36.4	27.8	43
	35.1	26.3	30
2400	20.5	18.2	43
	26.4	20.8	42
	25.9	19.9	38

(a) Test rate 0.005 inch per inch per minute to yield, then 0.05 inch per inch per minute to failure. Analyses 10.2% W, 2.7% Zr, 0.007% C, 0.015% O, 0.0006% H, and 0.004% N.
(b) Average data from six tests.

TABLE A-85. TENSILE PROPERTIES OF ANNEALED Cb-752 SHEET (0.030 INCH) AT 2200 F[a][4]

Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1 Inch, per cent
	Heat 10[b]	
26.2	17.2	27
26.7	18.8	27
	Heat 11[c]	
34.2	22.8	29
31.7	20.6	33

(a) Annealed 1 hour at 2200 F. Test rate 0.005 inch per inch per minute to yield, then 0.02 inch per inch per minute to failure.

(b) Analyses 9.45% W, 2.45% Zr, 0.01% C, 0.027% O, 0.0024% H, and 0.004% N.

(c) Analyses 10.04% W, 3.23% Zr, 0.027% C, 0.047% O, 0.0043% H, and 0.004% N.

TABLE A-86. EFFECT OF ANNEALING ON THE TENSILE PROPERTIES OF Cb-752 SHEET (0.030 INCH) AT 2200 F[a][3]

1-Hour Annealing Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1 Inch, per cent
1900	35.5	30.1	28
	38.0	32.2	30
2000	34.9	27.4	30
	33.9	28.3	24
2100	32.6	28.1	31
	30.5	26.6	32
2200	33.1	28.5	29
	31.0	26.7	42

(a) Test rate 0.005 inch per inch per minute to yield, then 0.05 inch per inch per minute to failure.

TABLE A-87. ELEVATED-TEMPERATURE TENSILE PROPERTIES OF Cb-752 SHEET[a][3]

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1 Inch, per cent
2000	42.9	31.7	20
	41.4	31.3	15
2200	33.5	26.1	28
	29.6	25.8	22
	33.3	26.4	26
2400	23.1	18.2	49
	22.9	19.1	38

(a) Test rate 0.05 inch per inch per minute.

TABLE A-88. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF Cb-752 SHEET (0.030 INCH)[a][1]

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1 Inch, per cent
RT	83.6	69.9	24
1000	53.8	36.9	18
2000	42.0	23.4	25
2200	36.0	23.4	33
2400	26.9	18.4	32

(a) Test rate 0.005 inch per inch per minute to yield, then 0.05 inch per inch per minute to failure.

TABLE A-89. TRANSVERSE TENSILE PROPERTIES OF RECRYSTALLIZED Cb-752 SHEET (0.035 INCH) AT ROOM TEMPERATURE AND 2700 F[a][2]

Temperature, F	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 1 Inch, per cent
RT	85.3	70.5	24
	86.3	71.4	23
	89.8	75.9	21
2700	16.9	16.6	>51
	17.1	16.8	>51
	17.0	16.7	>56

(a) Recrystallized 1 hour at 2200 F. Test rate 0.005 inch per inch per minute to 0.6 per cent yield, then 0.05 inch per inch per minute to fracture. Analyses 9.4% W, 2.45% Zr, 0.0270% O, 0.004% N, 0.0024% H, and 0.0100% C.

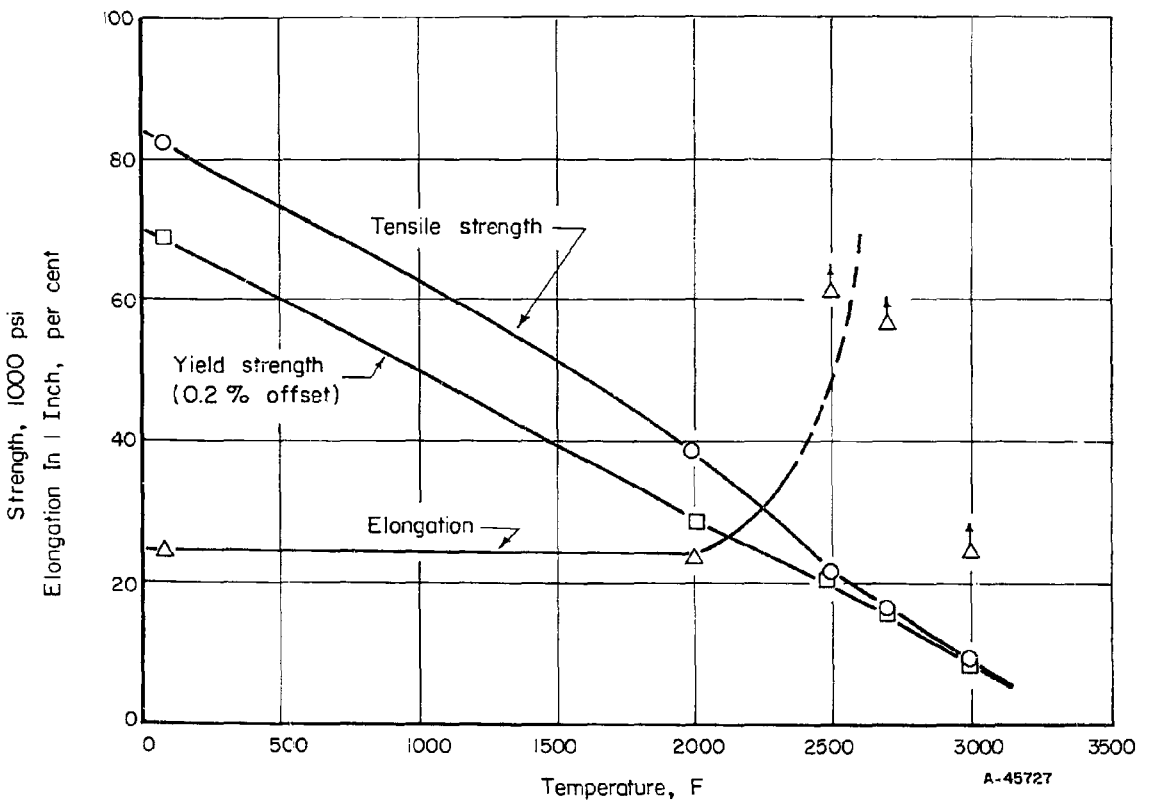


FIGURE A-68. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF RECRYSTALLIZED (1 HOUR 2200 F) Cb-752 SHEET (0.035 INCH)(2)

Test rate 0.005 inch per inch per minute to 0.6 per cent yield, then 0.05 inch per inch per minute to fracture.

Analyses 9.4% W, 2.45% Zr, 0.0270% O, 0.0040% N, 0.0024% H, and 0.0100% C.

TABLE A-90. DYNAMIC MODULUS OF ELASTICITY OF Cb-752 FROM ROOM TEMPERATURE TO 700 F[3]

Temperature, F	Dynamic Modulus of Elasticity, 10^6 psi
RT	15.03
100	15.02
200	15.00
300	14.98
400	14.95
500	14.90
600	14.87
700	14.48[a]

(a) Accuracy of this point is questionable.

TABLE A-91. ROOM-TEMPERATURE NOTCH TENSILE PROPERTIES OF Cb-752 SHEET[a][3]

Gage, inch	Tensile Strength, 100 psi	Yield Strength (0.2% Offset), 1000 psi
.012	73.9	68.2
	74.9	70.4
	75.9	69.3
	78.3	74.0
	77.4	69.1
.030	88.2	76.9
	85.7	75.9
	86.4	74.1
	86.9	76.5
	89.1	78.7

(a) K_t = 3.8 for 0.030-inch sheet. Test rate 0.005 inch per inch per minute to yield, then 0.05 inch per inch per minute to failure.

TABLE A-92. STRESS-RUPTURE PROPERTIES OF UPSET FORGED AND ANNEALED Cb-74[a][5]

Temperature, F	Stress, 1000 psi	Rupture Life, hours	Elongation in 1/2 Inch, per cent	Reduction in Area, per cent
2000	58	(b)	40	73
	48	0.1	57	76
	36	3.1	56	74
	31	8.0	46	81
2300	28	0.2	60	88
	24	0.6	80	84
	16	3.1	--	93
2600	15	0.7	56	75
	13	0.8	150	85
	10	1.3	108	91
	7	4.2	163	94

(a) Forged 75 per cent at 2200 F, annealed 1 hour at 2200 F. Nominal composition Cb-10W-5Zr.
(b) Broke on loading.

TABLE A-93. CREEP AND STRESS-RUPTURE PROPERTIES OF Cb-752 SHEET (0.030 INCH) AT 2200 F[1]

Stress, 1000 psi	Rupture Time, hours	Minimum Creep Rate, in./in./hr
20	1.0	0.19
18	12.7	0.0157
15	38.5	0.0034
14	106.1	0.0020
13	149.0	0.00083

TABLE A-94. RUPTURE CHARACTERISTICS OF Cb-752 SHEET (0.030 INCH) AT 2000 TO 2400 F[1]

Temperature, F	Average Initial Stress, 1000 psi, for Rupture		
	1 Hour	10 Hours	100 Hours
2000	27	22	18
2200	20	17	14
2400	15	11	8

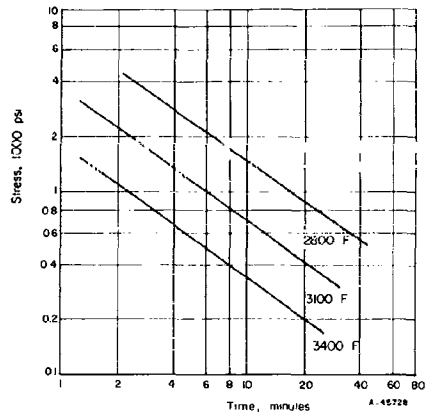


FIGURE A-69. TIME FOR 0.2 PER CENT CREEP AT VARIOUS STRESS LEVELS FOR Cb-74[7]

TABLE A-95. IMPACT BEND TEST DATA FOR RECRYSTALLIZED Cb-752 SHEET (0.035 INCH) AT ROOM TEMPERATURE[a][2]

Test	Condition	Energy Absorbed on Impact, ft-lb	Results
1	Recrystallized 1 hour at 2200 F	0.96	Ductile bend
2		1.02	Ductile bend
3		1.04	Ductile bend
4		0.90	Ductile bend
5		1.18	Ductile bend
	Average	1.02	
6	Recrystallized 1 hour at 2800 F	1.34	Ductile bend
7		1.27	Ductile bend
8		1.23	Ductile bend
9		1.37	Ductile bend
10		1.45	Ductile bend
	Average	1.33	

(a) Bent over 4T radius, 55-degree angle, using a 2-lb hammer at 11 feet per second. Analyses 9.4% W, 2.45% Zr, 0.0270% O, 0.0040% N, 0.0024% H, and 0.0100% C.

TABLE A-96. SHEAR STRENGTH OF Cb-752 SHEET (0.030 INCH) FROM ROOM TEMPERATURE TO 2400 F[a][3]

Temperature, F	Shear Strength, 1000 psi	Shear Yield Strength, (0.2% Offset), 1000 psi	Per Cent of Tensile Strength (Average)
RT	67.2	42.0	
	65.1	41.6	85
	68.8	43.0	
1000	42.5	36.6	
	43.5	34.5	60
	42.7	32.8	
2200	26.5	15.5	
	26.3	18.3	75
	28.3	12.3	
2400	20.3	13.4	
	21.2	12.8	78
	22.0	16.3	

(a) Test rate 0.005 inch per inch per minute to yield, then 0.05 inch per inch per minute to failure.

TABLE A-97. BEARING STRENGTH OF Cb-752 SHEET (0.030 INCH) FROM ROOM TEMPERATURE TO 2400 F[a][3]

Temperature, F	Bearing Strength, 1000 psi	Bearing Yield Strength (0.2% Offset), 1000 psi
RT	100.9	93.1
	104.2	92.0
	100.4	90.5
1000	83.8	67.8
	83.7	70.9
	83.2	81.1
2200	46.5	39.4
	62.5	47.8
	68.1	50.6
2400	41.7	22.1
	42.9	22.5
	39.6	22.3

(a) The effective bearing area was taken as product of the hole diameter and the thickness of the test specimen. Test rate 0.005 inch per inch per minute to yield, then 0.05 inch per inch per minute to failure.

4. Metallurgical Properties

a. Fabricability: can be readily fabricated using most conventional fabrication practices and procedures, primary ingot breakdown must be be done above the recrystallization temperature, while subsequent working to final forms may be done cold[4]

b. Transition temperature: Table A-9

c. Weldability: ductile welds are formed by conventional refractory-metal welding techniques; welds can be bent over a 2T radius, both parallel and normal to the weld, at room temperature without exhibiting any cracking; weld strength efficiencies of 94 per cent can be achieved[1]

d. Stress-relief temperature: 1 hour at 1800 F[2]

e. Recrystallization temperature: effect of annealing temperature on recrystallization and hardness of extrusions[5]

Temperature, F	Recrystallization, per cent	Hardness, VHN
As extruded	0	260
2200	10	244
2300	25	227
2400	90	240
2500	100	238
2600	100	228
2700	100	232

Note: Data for Cb-74, nominal composition Cb-10W-5Zr.

Table A-99
Figure A-70

TABLE A-98. BEND-TRANSITION BEHAVIOR FOR RECRYSTALLIZED Cb-752 SHEET[a][2]

Condition	Temperature, F	Results
	Heat 6313, 0.010 Inch[b]	
Recrystallized, 1 hr 2200 F	-320	Ductile
	-320	Ductile
	-320	Ductile
Recrystallized, 1 hr 2800 F	-320	Brittle
	-320	Brittle
	-275	Brittle
	-250	Brittle
	-225	Ductile
	-225	Brittle
	-200	Ductile
	-200	Ductile
	Heat 6310, 0.035 Inch[c]	
Recrystallized, 1 hr 2200 F	-320	Ductile
	-320	Ductile
	-320	Ductile
Recrystallized, 1 hr 2800 F	-320	Brittle
	-250	Brittle
	-200	Brittle
	-175	Brittle
	-150	Ductile
	-150	Ductile
	-150	Ductile

(a) Ram rate 10 inches per minute, bend angle 90 to 120 degrees after spring back.
(b) Analyses 8.48% W, 1.90% Zr, 0.0290% O, 0.0050% N, 0.0031% H, and 0.0200% C.
(c) Analyses 9.4% W, 2.45% Zr, 0.0270% O, 0.0040% N, 0.0024% H, and 0.0100% C.

TABLE A-99. HARDNESS AND GRAIN SIZE OF ANNEALED Cb-752 SHEET[a][3]

Heat	Gage, inch	ASTM Grain Size	Hardness, DPH
7	.012	9	195
	.018	10	186
	.030	10	209
8	.012	8	209
	.018	8	213
	.030	9	224
17	.012	9	195
	.018	9	196
	.030	9	196

(a) Annealed 1 hour at 2200 F. Analyses are as follows:

Heat	Composition, weight per cent					
	W	Zr	C	O	H	N
7	10.06	2.45	0.004	0.005	0.0006	<0.010
8	10.49	2.54	0.003	0.004	0.0007	<0.010
17	10.20	2.46	0.002	0.010	0.0006	<0.010

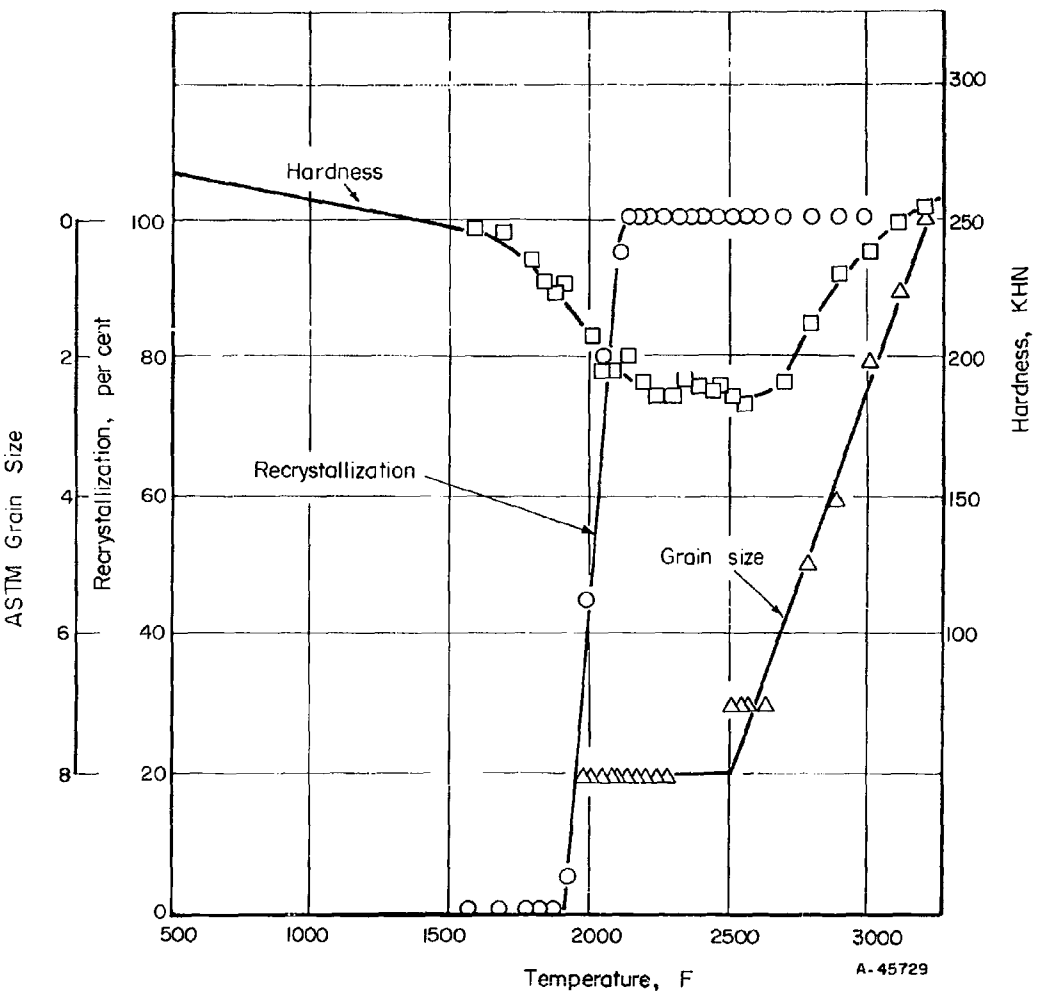


FIGURE A-70. RECRYSTALLIZATION CHARACTERISTICS OF Cb-752[2]

Analyses 9.40% W, 2.45% Zr, 0.0270% O, 0.0040% N, 0.0024% H and 0.0100% C.

References

(1) "Haynes Alloy Cb-752", New Product Data, Haynes Stellite Co. (1962).

(2) Baggerly, R. G., and Torgersen, R. T., "Evaluation of Cb-752 Columbium Alloy (Cb-10% W-2.5% Zr)", The Boeing Co., Document No. D2-35105 (1963).

(3) Bewley, J. G., "Final Report on Development of Methods to Produce Columbium Alloy Cb-74 (Renumbered Haynes Alloy Cb-752) Sheet", Haynes Stellite Co., ASD-TDR-63-201 (January, 1963).

(4) "Summary of Current Status of Development on HAYNES alloy Cb-752", Haynes Stellite Co. (March 20, 1962).

(5) Carson, R. O., "The Development Optimum Manufacturing Methods for Columbium Alloy Forgings", Crucible Steel Co. of America, Contract No. AF 33(600)-39944, ASD Interim Report 7-782 (V) (August 1961).

(6) Personal communication with G. P. Trost, Metals and Controls, Inc., regarding "Development of Optimum Processing Parameters for Refractory Metal Foil," Contract No. AF 33(657)-9384 (June, 1963).

(7) Moorhead, P. E., "Tensile and Creep Properties of Columbium, Tantalum, and Titanium Alloys at Elevated Temperature", Bell Aerosystems Co., Report BLR 62-26 (M) (December, 1962).

Cb-10W-10Hf

1. Identification of Material

   a. Designation: C-129 (Wah Chang)

   b. Chemical composition: typical analyses of arc-cast material[1]

Element	Weight Per Cent
W	9-11
Hf	9-11
O	<0.0300
N	<0.0150
H	<0.0020
C	<0.0100
Cb	Balance

   c. Forms available: ingot and most mill products[1]

2. Physical Properties

   a. Density: 0.343 lb/in.^{3} (calculated)[1]

3. Mechanical Properties

   a. Tensile Properties at Room Temperature

      Ultimate tensile strength: Tables A-100 and A-101

      Tensile yield strength: Tables A-100 and A-101

      Elongation: Tables A-100 and A-101

      Modulus of elasticity: 16.0×10^6 psi[1]

   b. Effect of Temperature on Tensile Properties

      Ultimate tensile strength: Table A-102

      Tensile yield strength: Table A-102

      Elongation: Table A-102

      Modulus of elasticity: data given below[1]

Temperature, F	Modulus of Elasticity, 10^6 psi
RT	16.0
2000	13.3
2500	12.2
2700	10.4
3000	8.1

c. Creep and Stress-Rupture Properties

Figure A-71

d. Other Selected Mechanical Properties

Bend ductility: for sheet (0.030 to 0.040 inch) material at room temperature tested at a ram rate of 10 inches per minute[1]

Condition	Bend Ductility
Stress relieved, 1 hr 1800 F	120 degree 1T bend
Recrystallized, 1 hr 2400 F	120 degree 1T bend
Recrystallized, 1 hr 2800 F	120 degree 1T bend

Impact: impact bend test results for sheet material at room temperature[2]

Condition	Impact Energy Absorbed, ft-lb
Stress relieved, 1 hr 1800 F	1.70
Recrystallized, 1 hr 2400 F	1.39
Recrystallized, 1 hr 2800 F	1.41

TABLE A-100. ROOM-TEMPERATURE TENSILE PROPERTIES OF ARC-CAST C-129 SHEET

Condition	Sheet Thickness, inch	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1 Inch, per cent	Reference
Cold rolled[a]	0.030	130.8 (L) 142.6 (T)	122.2 (L) 126.8 (T)	4 (L) 3 (T)	(2) (2)
Stress relieved (1 hr 1800 F)[a]	0.030	112.3 (L) 113.9 (T)	100.5 (L) 103.7 (T)	16 (L) 13 (T)	(2) (2)
Stress relieved[b]	--	109.3	101.8	14	(1)
Recrystallized (1 hr 2400 F)[b]	0.010	81.0	70.1	21	(1)
Recrystallized (1 hr 2400 F)[a]	0.030	84.7 (L) 88.2 (T)	70.7 (L) 73.5 (T)	30 29	(2) (2)
Recrystallized (1 hr 2400 F)[b]	0.030	88.3	72.2	26	(1)
Recrystallized (1 hr 2400 F)[b]	0.040	88.5	71.5	26	(1)

(a) Average values for two tests. Test rate 0.005 inch per inch per minute to 0.6 per cent strain, then 0.05 inch per inch per minute to fracture. Analyses 9.6-10.4% W, 8.72-9.64% Hf, 0.0030% C, 0.0030-0.0034% N, 0.0003% H, and 0.0080-0.0230% O.

(b) Typical analyses 9-11% W, 9-11% Hf, <0.0300% O, <0.0150% N, <0.0020% H, <0.0100% C, bal Cb.

TABLE A-101. ROOM-TEMPERATURE TENSILE PROPERTIES OF C-129 REROLL STOCK AND FINISHED FOIL[a][3]

Coil Identification	Gage, inch	Recrystallization, per cent	ASTM Grain Size	Test Direction	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 2 Inches, per cent
			Reroll Foil Stock				
129-1, -2, -3	0.050	100	5.0	L	90.8	71.2	30.0
				T	91.4	71.5	30.0
			Finished Foil				
129-2	0.012	100	7.5	L	92.1	72.1	26.5
				T	92.0	73.4	27.0
129-3	0.012	100	8.0	L	90.8	73.0	29.5
				T	94.2	76.0	28.5
129-1	0.006	100	9.0	L	91.0	74.7	22.0
				T	93.1	76.3	28.8

(a) Test rate 0.005 inch per inch per minute to 0.2 per cent yield, then 0.05 inch per inch per minute to failure. Analyses are as follows:

Coil Identification	Gage, inch	Weight Per Cent			PPM			
		W	Hf	Zr	O	N	C	H
			Reroll Foil Stock					
129-1, 2, 3	0.050	10.9	9.7	0.3	60	88	95	<5
			Finished Foil					
129-2	0.012	--	--	--	140	68	125	<5
129-3	0.012	--	--	--	120	57	110	<5
129-1	0.006	--	--	--	125	68	90	<5

TABLE A-10[illegible]. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF ARC-CAST C-129 SHEET

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1 Inch, per cent
	Stress Relieved 1 Hour at 1800 F, 0.030 Inch[a][2]		
RT	112.3 (L)	100.5 (L)	16 (L)
	113.9 (T)	103.7 (T)	13 (T)
600	88.0	72.7	9
1200	83.2	76.2	6
2000	47.8	39.6	30
2500	21.1 (L)	19.8 (L)	>65 (L)
	21.8 (T)	20.3 (T)	>73 (T)
2700	17.9	17.3	>47
3000	11.9	11.2	>49
	Stress Relieved 1 Hour at 1800 F[b][1]		
RT	109.3	101.8	14
2000	49.0	36.6	28
2500	20.7	16.9	>67
2700	15.2	14.8	>41
3000	9.8	9.3	>51
	Recrystallized 1 Hour at 2400 F, 0.010 Inch[b][1]		
RT	81.0	70.1	21
2000	40.8	30.6	5
2500	24.0	22.2	>40
2700	19.1	18.5	62
3000	12.8	12.6	61
	Recrystallized 1 Hour at 2400 F, 0.030 Inch[a][2]		
RT	84.7 (L)	70.7 (L)	30 (L)
	88.2 (T)	73.5 (T)	29 (T)
600	59.0	45.4	24
1200	59.1	36.1	17
2000	39.2	29.1	42
2500	21.8 (L)	20.1 (L)	>37
	22.0 (T)	20.5 (T)	>57
2700	18.3	17.5	>59
3000	12.3	11.6	>54
	Recrystallized 1 Hour at 2400 F, 0.030 Inch[b][1]		
RT	88.3	72.2	26
2000	45.6	30.5	25
2500	24.4	22.1	>53
2700	19.7	18.4	>41
3000	10.5	10.4	>62

TABLE A-102. (Continued)

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1 Inch, per cent
	Recrystallized Hour at 2100 F, 0.040 Inch[b](1)		
RT	88.5	71.5	26
2000	48.4	31.2	27
2500	26.1	23.1	>67
2700	20.4	18.1	41
2700	18.9	18.6	>71
3000	10.3	10.2	>62
3000	10.7	10.6	62

(1) Average values for two tests. Test rate 0.005 inch per inch per minute to 0.6 per cent strain, then 0.05 inch per inch per minute to fracture. Analyses 9.6-10.4% W, 8.72-9.64% Hf, 0.0030% C, 0.0030-0.0034% N, 0.0003% H, and 0.0080-0.0230% O.

(2) Typical analyses 9-11% W, 9-11% Hf, <0.0300% O, <0.0150% N, <0.0020% H, <0.0100% C, bal Cb.

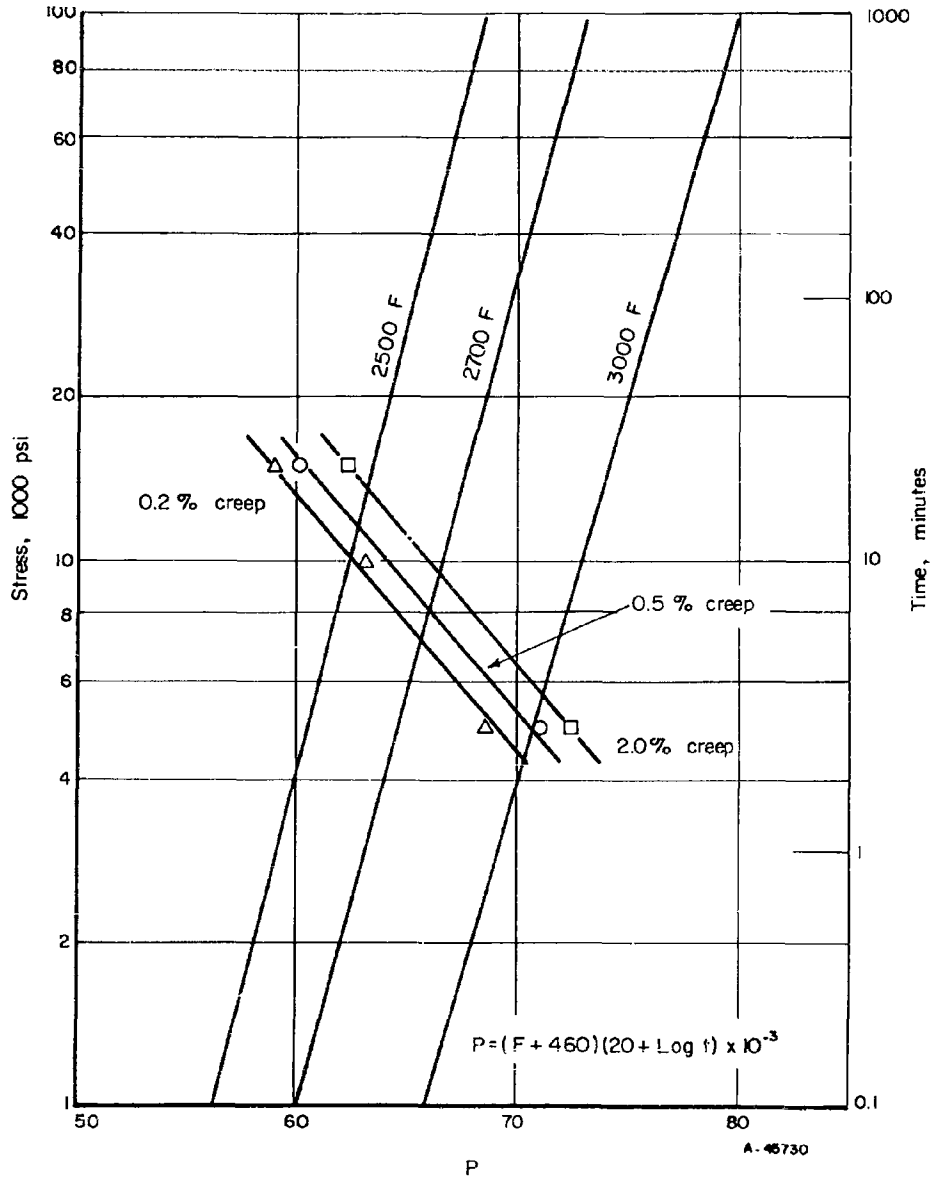


FIGURE A-71. CREEP PROPERTIES OF ARC-CAST C-129(1)

Typical analyses 9-11% W, 9-11% Hf, <0.0300% O, <0.0150% N, <0.0020% H, <0.0100% C, bal Cb.

4. Metallurgical Properties

a. Fabricability: arc-melted ingot can readily be hot extruded or forged to sheet bar; warm intermediate rolling is done at 800 F followed by finish rolling at room temperature[1]

b. Transition temperature: for sheet (0.030 to 0.040 inch) material bend tested at a 4T bend radius and 10 inches per minute ram rate[1]

	Transition Temperature, F	
	4T	Brittle
Stress relieved, 1 hr 1800 F	<-320	<-320
Recrystallized, 1 hr 2400 F	-275	-300
Recrystallized, 1 hr 2800 F	-200	-250

c. Weldability: readily weldable using the TIG process; however, solution annealing is required to restore good ductility[1]

d. Stress-relief temperature: 1 hour at 1800 F[1]

e. Recrystallization temperature: Figure A-72

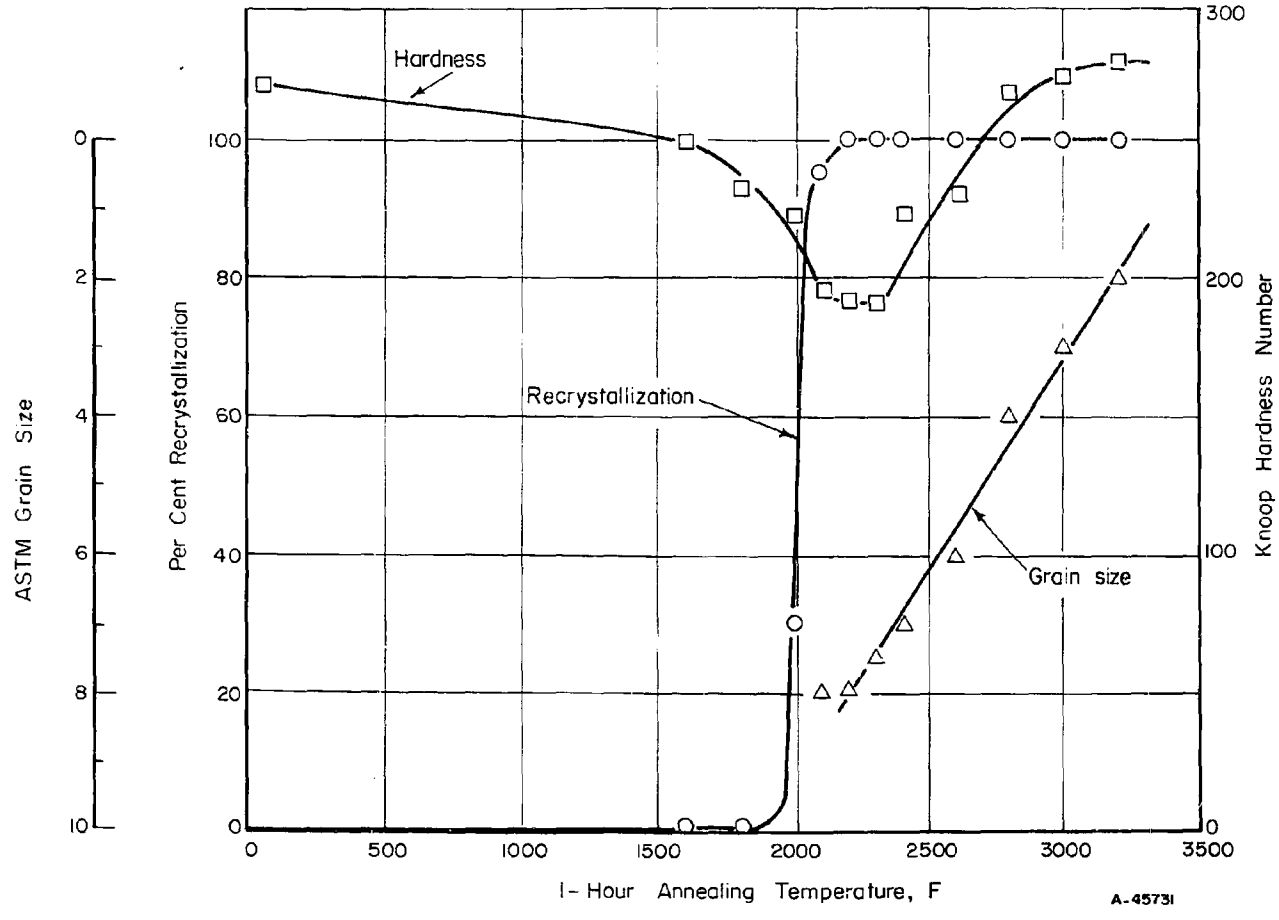


FIGURE A-72. RECRYSTALLIZATION BEHAVIOR OF COLD-ROLLED C-129 SHEET (0.030 to 0.040 INCH)[1,2]

References

(1) "Columbium and Tantalum Base Alloys for Structural and Nuclear Application", Wah Chang Corp., Vol 1, Rev. 2 (1962).

(2) Torgerson, R. T., "Development and Properties of Columbium - 10% Tungsten - 10% Hafnium Alloy", The Boeing Co., Technical Paper presented at the 1962 Fall Meeting of the Metallurgical Society of AIME, New York (October 29 to November 1, 1962).

(3) Personal Communication with G. P. Trost, Metals and Controls, Inc., regarding "Development of Optimum Processing Parameters for Refractory Metal Foil", Contract No. AF 33(657)-9384 (June, 1963).

Cb-15W-5Mo-1Zr

1. Identification of Material

   a. Designation: F-48 (General Electric)
      D-40 (Du Pont)

   b. Chemical Composition: Table A-103

   c. Forms available: ingot and fabricated shapes on a best efforts basis

TABLE A-103. SELECTED CHEMICAL ANALYSES OF F-48

	Amount Present, weight per cent													
		Ingot												
Element	Nominal, Ref. (1)[a]	Top, Ref. (2)[a]	Bottom, Ref. (2)[a]	Top, Ref. (2)[b]	Bottom, Ref. (2)[b]	Top, Ref. (2)[a]	Bottom, Ref. (2)[a]	Top, Ref. (3)[c]	Bottom, Ref. (3)[c]	Top, Ref. (3)[a]	Bottom, Ref. (3)[a]	Plate, Ref. (2)[d]	Plate, Ref. (4)[d]	Rod, Ref. (5)[a]
Cb	--	--	--	--	--	--	--	--	--	--	--	--	79.1-79.8	--
W	15	15.7	15.3	15.6	15.7	13.8	14.5	13.9	13.7	16.0	15.6	12.4	14.0-15.1	15-16
Mo	5	5.2	5.2	4.6	4.8	4.7	4.8	5.02	4.67	4.93	4.75	3.9	4.9-5.2	5.0-5.2
Zr	1	0.99	1.10	0.97	0.99	0.92	0.98	0.90	0.89	1.16	1.03	1.0	1.04-1.13	1.0-1.4
Ta	--	--	--	--	--	--	--	--	--	--	--	--	0.10-0.125	--
C	0.04-0.08	0.0443	0.0320	0.0320	0.0430	0.0290	0.0330	0.038	0.036	0.020	0.026	0.0232	0.035-0.039	0.0200-0.0400
N	--	0.0013	0.0057	0.0041	0.0085	0.0017	0.0037	0.018	0.016	0.023	0.018	0.0036	0.001-0.002	0.0200-0.0350
O	0.03-0.06	0.0210	0.0150	0.0180	0.0270	0.0210	0.0190	0.050	0.016	0.017	0.019	0.0109	0.071-0.085	0.0200-0.0500
H	--	--	--	--	--	--	--	--	--	--	--	---	0.0002-0.0004	--

(a) General Electric material.
(b) Allegheny Ludlum material.
(c) Wah Chang material.
(d) Du Pont material, D-40.

2. Physical Properties

   a. Melting point: 4500 F (estimated)[1]

   b. Density: 0.34 lb/in.^{3}[1]

   c. Thermal expansion: Figures A-73 through A-75

   d. Thermal conductivity: Figures A-76 and A-77

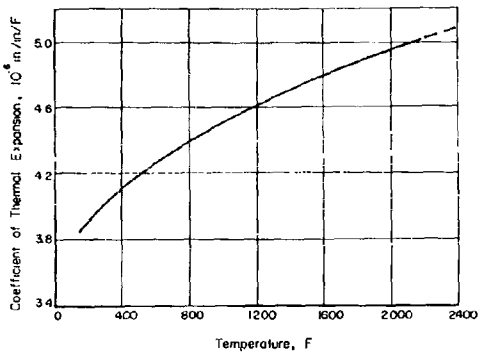


FIGURE A-73. COEFFICIENT OF THERMAL EXPANSION OF F-48

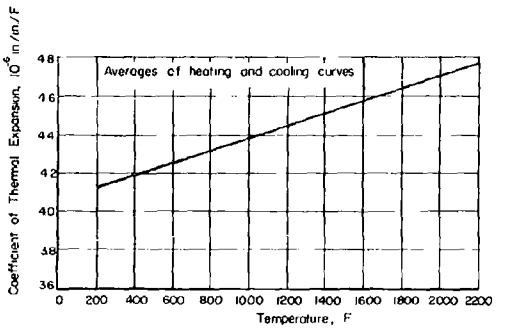


FIGURE A-74. MEAN COEFFICIENT OF THERMAL EXPANSION OF F-48[3]

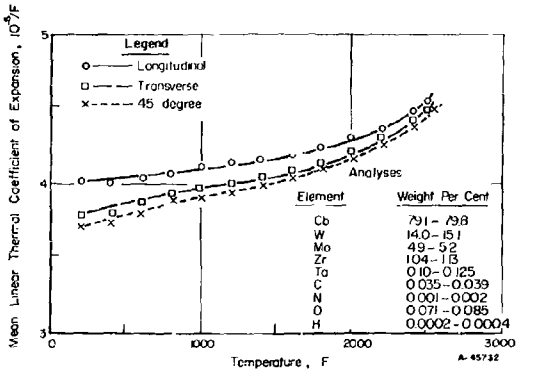


FIGURE A-75. THERMAL EXPANSION OF D-40 IN THE LONGITUDINAL, TRANSVERSE, AND 45-DEGREE DIRECTIONS[4]

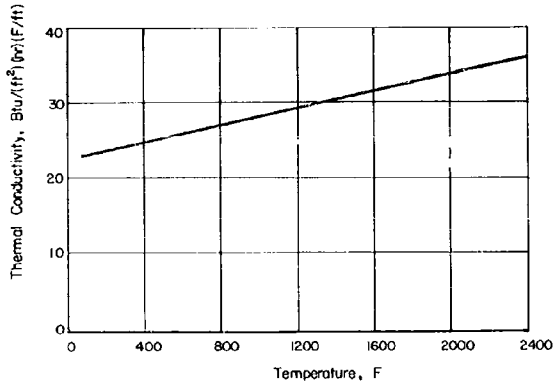


FIGURE A-76. THERMAL CONDUCTIVITY OF F-48[1]

Estimated data.

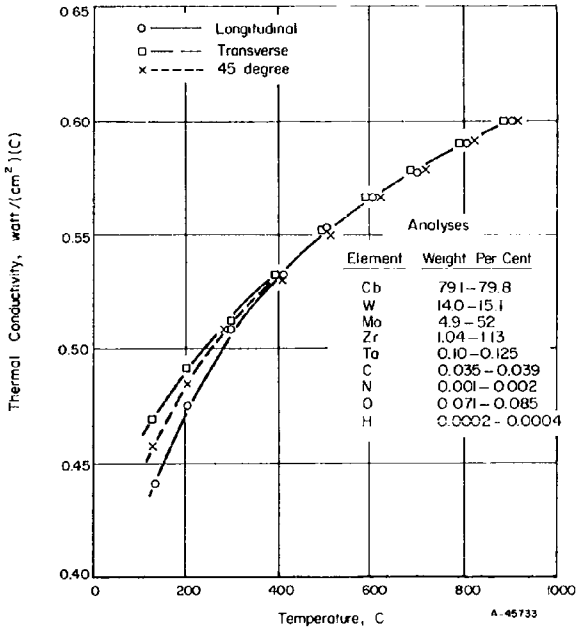


FIGURE A-77. THERMAL CONDUCTIVITY OF D-40 IN THE LONGITUDINAL, TRANSVERSE, AND 45-DEGREE DIRECTIONS[4]

3. Mechanical Properties

a. Tensile Properties at Room Temperature

Ultimate tensile strength: Tables A-104 through A-108

Tensile yield strength: Tables A-104 through A-108

Elongation: Tables A-104 through A-108

Reduction in area: Tables A-104 through A-106

Modulus of elasticity: 25×10^6 psi[1]

b. Effect of Temperature on Tensile Properties

Ultimate tensile strength: Tables A-109 through A-112
Figures A-78 through A-82

Tensile yield strength: Tables A-109 through A-112
Figures A-78 through A-81

Elongation: Tables A-109 through A-112
Figures A-78 through A-82

Reduction in area: Tables A-106, A-109, and A-110

Modulus of elasticity: Table A-113
Figures A-83 and A-84

c. Notched Tensile Properties: Table A-114
Figures A-85 and A-86

d. Creep and Stress-Rupture Properties: Tables A-106, A-115, and A-116
Figures A-87 through A-94

e. Other Selected Mechanical Properties

Impact: Figure A-95

Bend ductility: for stress-relieved (1 hour 2200 F) material[3]

Specimen Orientation	Number of Tests	Spring Back From a 105-Degree Bend, degrees	Remarks
Longitudinal	4	7-12	No cracking
Transverse	4	6-10	Slight to severe cracking
45 degree	2	7-10	No cracking to slight cracking

Shear strength: data at room temperature and 1600 F have been determined for fastener material[8]

Type Fastener	Diameter, inch	Shear Strength, 1000 psi RT	Shear Strength, 1000 psi 1600 F
Bolt and nut	0.250	80.0	46.5
		--	46.0
Solid rivet	0.125	84.0	55.0
		89.5	54.5

Table A-117

Bearing strength: Table A-118

TABLE A-104. ROOM-TEMPERATURE TENSILE PROPERTIES OF ANNEALED F-48 UPSET FORGINGS[a][6]

Forging Temperature, F	Upset Reduction, per cent	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent
2300[b]	48	119.2	99.9	10	7
2500	47	109.0	95.9	3	1
2700	47	112.7	99.5	2	3
2700[b]	47	112.5	91.2	10	12
2300	72	111.7	99.7	0	1
2500	71	110.4	99.5	5	8
2700[b]	70	120.1	99.4	26	23
2700	72	116.7	91.7	10	14
2700[b]	72	110.3	85.6	25	38

(a) Annealed 1 hour at 2500 F.
(b) Annealed 1/2 hour at 1400 F prior to testing.

TABLE A-105. ROOM-TEMPERATURE TENSILE PROPERTIES OF D-40 PLATE [a][4]

Heat	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1/2 Inch, per cent	Reduction in Area, per cent
152	106.4	95.4	14	33.0
	99.5	89.7	6	10.5
154	103.8	97.8	4	8.8
	102.5	95.5	2	5.6
155	117.4	96.3	4	7.1
	107.3	100.3	11	29.5
156	108.7	97.3	8	13.1
	97.1	97.1	0	0
157	107.8	94.4	6	16.4
	114.4	98.2	6	9.0
158	107.7	96.8	8	16.1
	106.1	96.8	22	44.3
159	105.0	96.5	1	1.7
161	106.4	103.2	2	2.4
	105.8	100.0	4	7.2
162	114.2	101.7	12	25.0
	111.7	100.0	4	16.1
163	110.2	99.4	8	20.5
	108.2	104.4	2	2.5
166	114.3	94.0	14	18.3
	113.4	93.1	13	17.1
174	117.3	105.2	10	12.1
	118.2	105.2	12	17.8
175	113.4	101.2	8	14.8
	116.8	100.5	12	23.8
215	108.3	101.1	2	4.0
	103.2	99.7	4	12.9
216	106.1	97.3	8	12.9
	103.2	98.8	2	2.4
217	109.7	100.2	16	44.3
	104.5	101.8	0	4.1
Average	108.7	98.6	7.3	14.3

(a) Tested transverse to the extrusion direction. Test rate 0.05 inch per minute crosshead speed. Chemical analyses for material tested are given in Table A-106.

TABLE A-106. CHEMICAL ANALYSES OF D-40 PLATE USED TO OBTAIN DATA GIVEN IN TABLES A-105 AND A-110 AND FIGURES A-87 AND A-88

Heat	Element, weight per cent							
	Cb	W	Mo	Zr	Ta	C	N	O
152	79.6	14.5	4.89	0.99	0.36	.039	.002	.0038
154	78.9	15.0	4.82	1.01	0.36	.051	.001	.0046
155	79.7	13.3	4.99	0.98	0.49	.044	.004	.0052
156	79.4	14.6	4.87	1.01	0.24	.039	.003	.0073
157	79.8	14.0	5.10	1.04	0.145	.043	.004	.0051
158	79.7	14.3	4.88	0.98	0.27	.039	.002	.0048
159	79.8	15.0	4.91	1.01	0.50	.043	.002	.0068
161	79.1	14.5	4.88	0.99	0.31	.038	.002	.0066
162	80.0	14.5	5.05	1.00	0.53	.033	.007	.0045
163	80.0	14.3	5.00	1.01	0.53	.039	.019	.0043
166	81.3	12.8	5.14	1.02	0.16	.041	.002	.0035
174	79.2	14.3	5.00	0.98	0.27	.030	.001	.0076
175	80.0	14.5	4.95	1.01	0.53	.037	.005	.0054
215	79.6	14.5	4.98	0.93	0.53	.033	.005	.0074
216	80.5	13.1	5.03	0.99	0.39	.037	.005	.0060
217	79.6	14.1	5.01	1.01	0.27	.036	.005	.0080

TABLE A-107. EFFECT OF STRAIN RATE ON THE ROOM-TEMPERATURE TENSILE PROPERTIES OF STRESS-RELIEVED F-48 SHEET (0.045 INCH)[a][3]

Crosshead Speed, in./min	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1 inch, per cent
0.2	120	100	16.5
5	129	125	13.3
10	132	131.7	13.3

(a) Stress relieved 1 hour at 2200 F.

TABLE A-108. EFFECT OF TEST DIRECTION ON THE TENSILE PROPERTIES OF F-48 SHEET AT ROOM TEMPERATURE[3]

Sheet Thickness, inch	Property	Test Direction		
		Longitudinal	Transverse	45 Degree
0.010	Tensile Strength, 1000 psi	135	128	124
	Yield Strength (0.2% Offset), 1000 psi	61	77	61
	Elongation in 3/4 Inch, per cent	6	5	12
0.044	Tensile Strength, 1000 psi	110	112	38
	Yield Strength, (0.2% Offset), 1000 psi	99	102	--
	Elongation in 3/4 Inch, per cent	13	8	0
0.048	Tensile Strength, 1000 psi	--	115	93
	Yield Strength, (0.2% Offset), 1000 psi	--	100	--
	Elongation in 3/4 Inch, per cent	--	9	0
0.051	Tensile Strength, 1000 psi	105	109	--
	Yield Strength (0.2 per cent Offset), 1000 psi	96	99	--
	Elongation in 3/4 Inch, per cent	14	9	--
0.060	Tensile Strength, 1000 psi	120	106	108
	Yield Strength (0.2% Offset), 1000 psi	107	104	99
	Elongation in 3/4 Inch, per cent	14	2	20

TABLE A-109. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF UFSET FORGED AND ANNEALED F-48[a][6]

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent
1000	86.6	--	26	68
2000	64.0	58.0	22	71
2300	50.0	46.0	30	88
2600	32.0	31.2	56	96

(a) Forged 75 per cent at 2500 F, annealed 1 hour at 2500 F.

TABLE A-110. TENSILE PROPERTIES OF D-40 PLATE AT 2200 F [a][4]

Heat	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 0.5 Inch, per cent	Reduction in Area, per cent
152	41.0	39.9	15.0	15.7
	40.8	37.0	28.0	38.7
154	42.3	40.8	18.0	28.2
	41.7	39.2	12.0	21.9
155	46.6	41.8	15.0	44.8
	44.9	41.8	20.0	42.4
156	40.1	36.9	6.0	6.6
	43.2	40.0	30.6	33.5
157	42.5	39.4	26.0	59.0
	43.6	39.9	13.0	43.4
158	41.2	35.6	30.0	70.6
	43.1	38.6	26.0	29.8
159	42.2	38.8	14.6	31.7
	42.0	38.0	23.9	34.2
161	43.1	38.9	24.0	37.5
	47.1	44.9	30.0	56.5
162	43.8	40.7	24.0	35.8
	41.4	34.4	28.0	64.1
163	41.5	37.1	18.0	26.3
	43.7	39.0	24.0	36.3
166	41.0	37.2	16.0	28.5
	39.2	33.9	14.8	19.1
174	49.5	46.9	--	70.3
	49.6	41.3	40.0	77.0
175	43.5	37.1	16.0	17.2
	48.1	43.7	20.0	46.1
215	41.8	34.5	20.0	45.8
	43.6	40.0	24.0	44.9
216	45.6	37.5	36.0	65.1
	44.0	37.6	22.0	47.1
217	45.7	43.6	--	45.2
	45.9	41.3	16.0	23.9
Average	43.5	39.2	21.6	40.2

(a) Tested transverse to the extrusion direction. Test rate 0.05 inch per minute crosshead speed. Chemical analyses for material tested are given in Table A-106.

TABLE A-111. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF STRESS-RELIEVED F-48 SHEET (0.049 INCH)[a][3]

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 3/4 Inch, per cent
RT	122.7	111.3	16.3
	121.9	109.5	16.3
	121.0	108.9	15.0
1000	86.5	77.8	8.8
1600	81.3	77.2	7.5
	83.0	75.7	7.5
	80.8	71.8	6.2
2200	40.2	36.9	41.3
2500	26.7	24.8	47.5
	27.8	25.8	47.0

(a) Stress relieved 1 hour at 2200 F. Test rate 0.005 inch per inch per minute to yield, then 0.03 inch per inch per minute to fracture.

TABLE A-112. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF STRESS-RELIEVED F-48 SHEET (0.040 INCH)[a][3]

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1 Inch, per cent
-65	136.5	125.0	17
	139.9	127.2	12
RT	121.0	100.0	16
	118.2	94.4	17
1000	79.1	75.8	8
	83.8	74.5	7
1600	78.5	72.5	8
	79.2	72.2	7
2000	65.3	59.0	9
	63.7	57.2	11
2200	53.1	45.5	16
	53.8	48.1	15
2350	45.2	39.0	20
	43.1	38.0	15
2500	32.3	27.9	36
	34.0	30.0	22
2700	24.8	22.8	55
	24.3	23.7	54

(a) Stress relieved 1 hour at 2200 F. Test rate 0.2 inch per minute crosshead speed.

TABLE A-113. EFFECT OF TEMPERATURE ON THE DYNAMIC MODULUS OF ELASTICITY OF F-48[a][3]

Temperature, F	Modulus of Elasticity, 10^6 psi
80	22.2
950	20.6
1180	18.1
1830	10.5
2060	7.5
2115	7.4
2250	7.3
2275	7.2
2425	7.1
2470	5.8
2550	4.6
2680	4.4
2795	1.4

(a) Since a compensating estimation was factored into the formula, these data may be somewhat inaccurate.

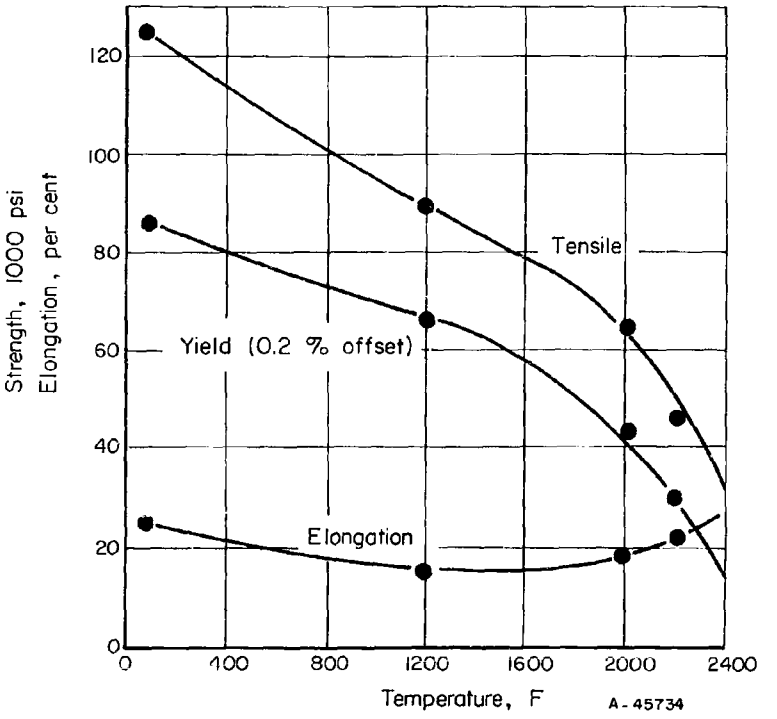


FIGURE A-78. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF EXTRUDED, SWAGED, AND STRESS-RELIEVED F-48 BAR STOCK[1]

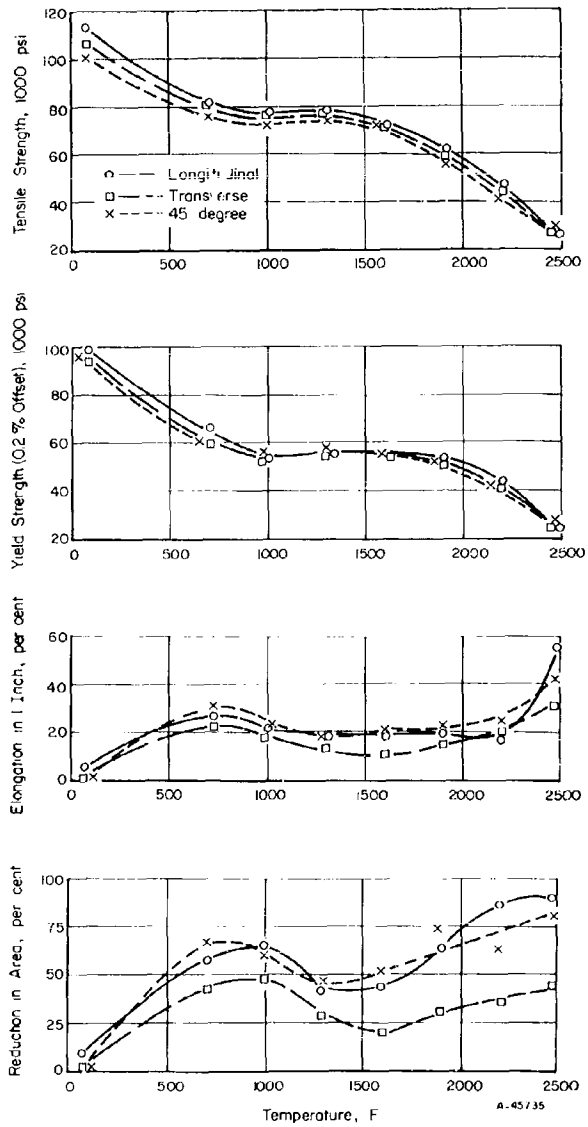


FIGURE A-79. EFFECT OF TEMPERATURE AND TEST DIRECTION ON THE TENSILE PROPERTIES OF D-40 PLATE[4]

Test rate 0.05 inch per minute crosshead speed.

Analyses 79.1-79.8% Cb, 14.0-15.1% W, 4.9-5.2% Mo, 1.04-1.13% Zr, 0.10-0.125% Ta, 0.035-0.039% C, 0.001-0.002% N, 0.071-0.085% O, and 0.0002-0.0004% H.

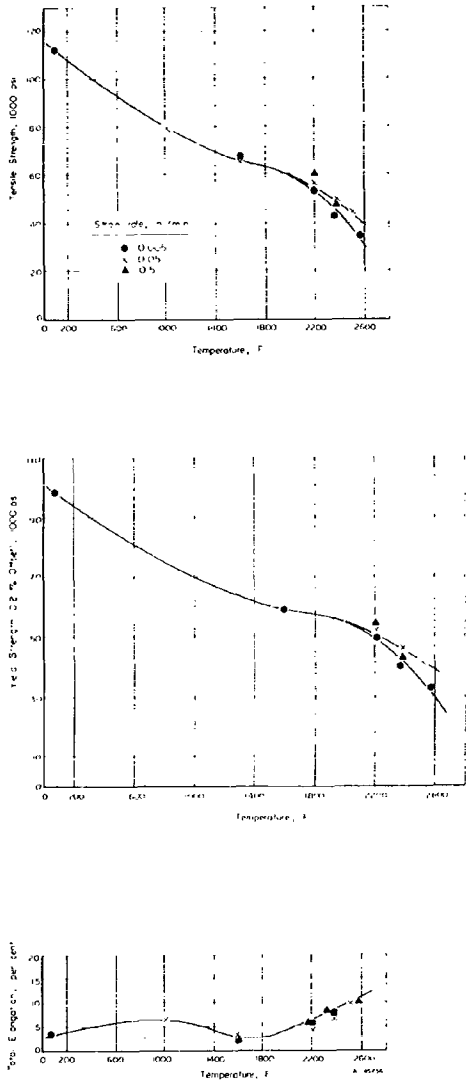
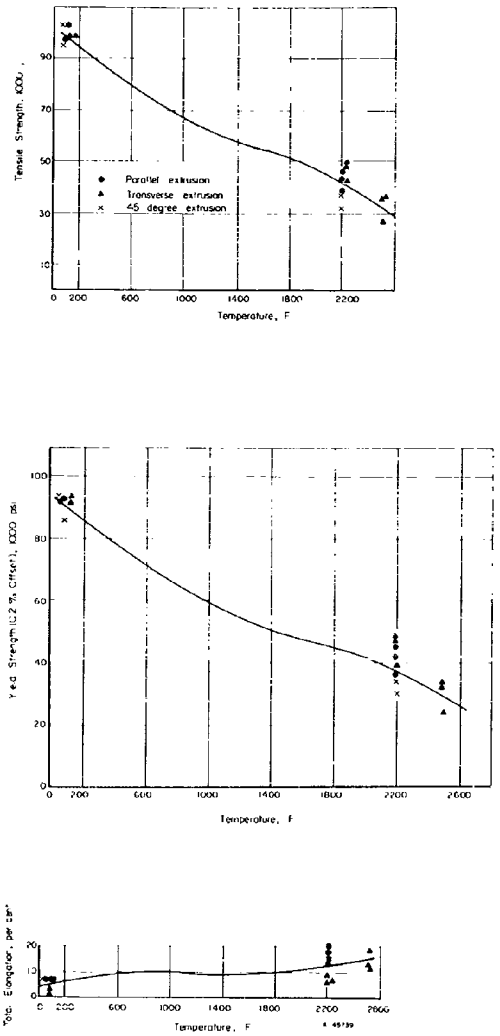


FIGURE A-80. EFFECT OF TEMPERATURE AND STRAIN RATE ON THE TENSILE PROPERTIES OF COATED F-48 TESTED IN AIR[2]

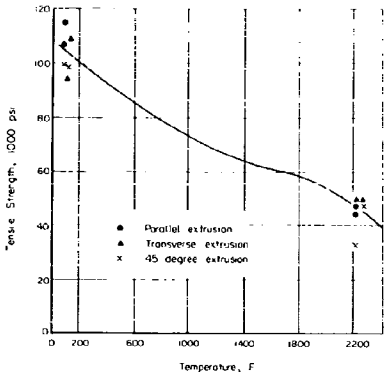
	Billet Chemistry					
	Weight Per Cent			PPM		
Location	W	Mo	Zr	C	O	N
Top	15.7	5.2	0.99	443	210	13
Bottom	15.3	5.2	1.10	320	150	57

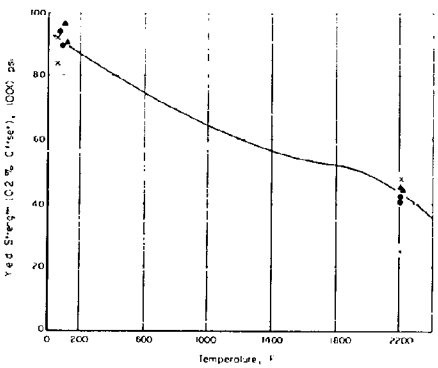


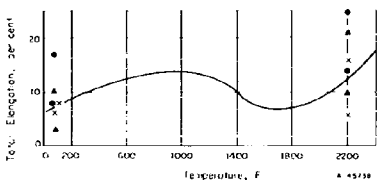
	Billet Chemistry					
	Weight Per Cent			PPM		
Location	W	Mo	Zr	C	O	N
Top	13.8	4.7	0.92	290	210	17
Bottom	14.5	4.8	0.98	330	190	37

FIGURE A-81. EFFECT OF TEMPERATURE AND TEST DIRECTION ON THE TENSILE PROPERTIES OF STRESS-RELIEVED F-48(2)

Test rate 0.005 per minute.



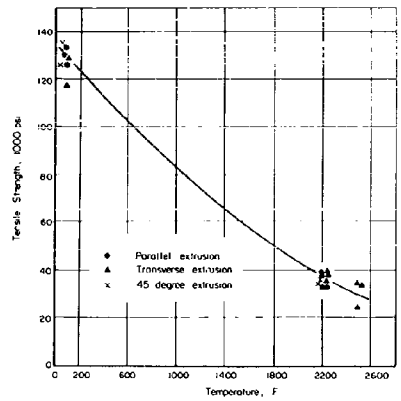


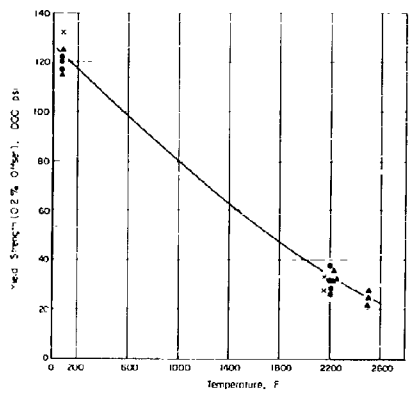


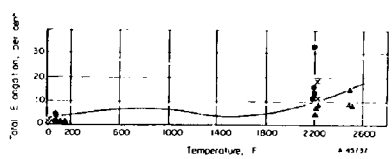
Billet Chemistry

Location	Weight Per Cent W	Mo	Zr	PPM C	O	N
Top	15.6	4.6	0.97	320	180	41
Bottom	15.7	4.8	0.99	430	270	85

FIGURE A-81. (CONTINUED)







	Weight Per Cent			PPM		
	W	Mo	Zr	C	O	N
Finished Plate	12.4	3.9	1.0	232	109	36

FIGURE A-81. (CONTINUED)

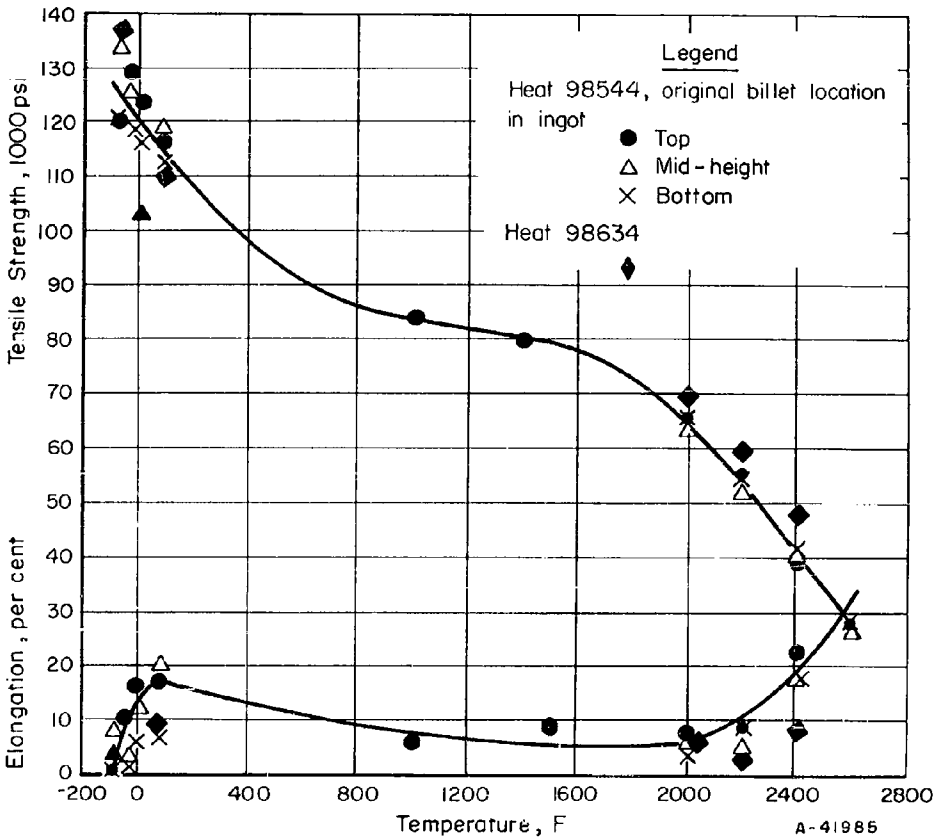


FIGURE A-82. EFFECT OF TEMPERATURE ON THE TRANSVERSE TENSILE PROPERTIES OF F-48 SHEET (0.035 INCH)[7]

Element	Average Composition Heat 98554	Heat 98634
W	14.54	14.37
Mo	4.21	5.10
Zr	0.91	0.95
C	0.0300	0.0320
O	0.0052	0.0040
N	0.0041	0.0040
H	0.0008	

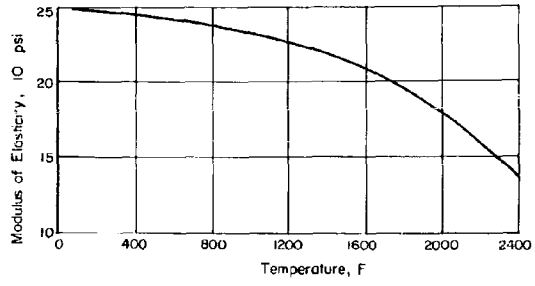


FIGURE A-83. EFFECT OF TEMPERATURE ON THE MODULUS OF ELASTICITY OF F-48 AS DETERMINED FROM STRESS-STRAIN MEASUREMENTS(1)

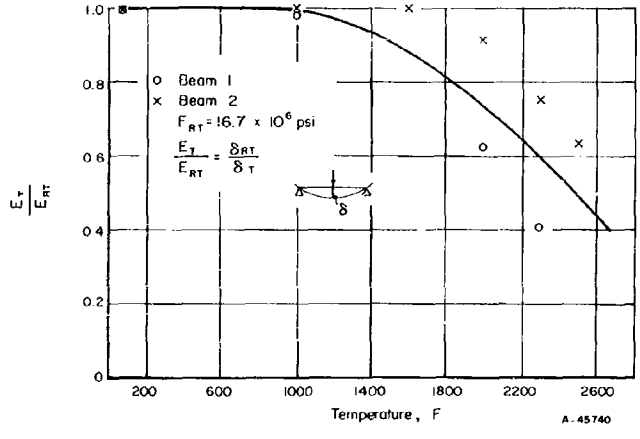


FIGURE A-84. EFFECT OF TEMPERATURE ON THE MODULUS OF ELASTICITY OF F-48 AS DETERMINED FROM DEFLECTION OF A SIMPLE BEAM WITH MID-SPAN LOADING(2)

TABLE A-114. ROOM-TEMPERATURE NOTCHED TENSILE PROPERTIES OF STRESS-RELIEVED F-48 SHEET (0.049 INCH)[a][3]

Notch Radius, inch	Notch Width, inch	K_t	Notched Tensile Strength, 1000 psi	Elongation in 3/4 Inch, per cent	Notched/Unnotched Tensile Strength Ratio
0.013	0.235	4.1	121.8	1.0	1.0
			119.9	1.0	0.99
0.003	0.423	8.3	106.1	2.0	0.88
			105.1	1.0	0.87

(a) Stress relieved 1 hour 2200 F.

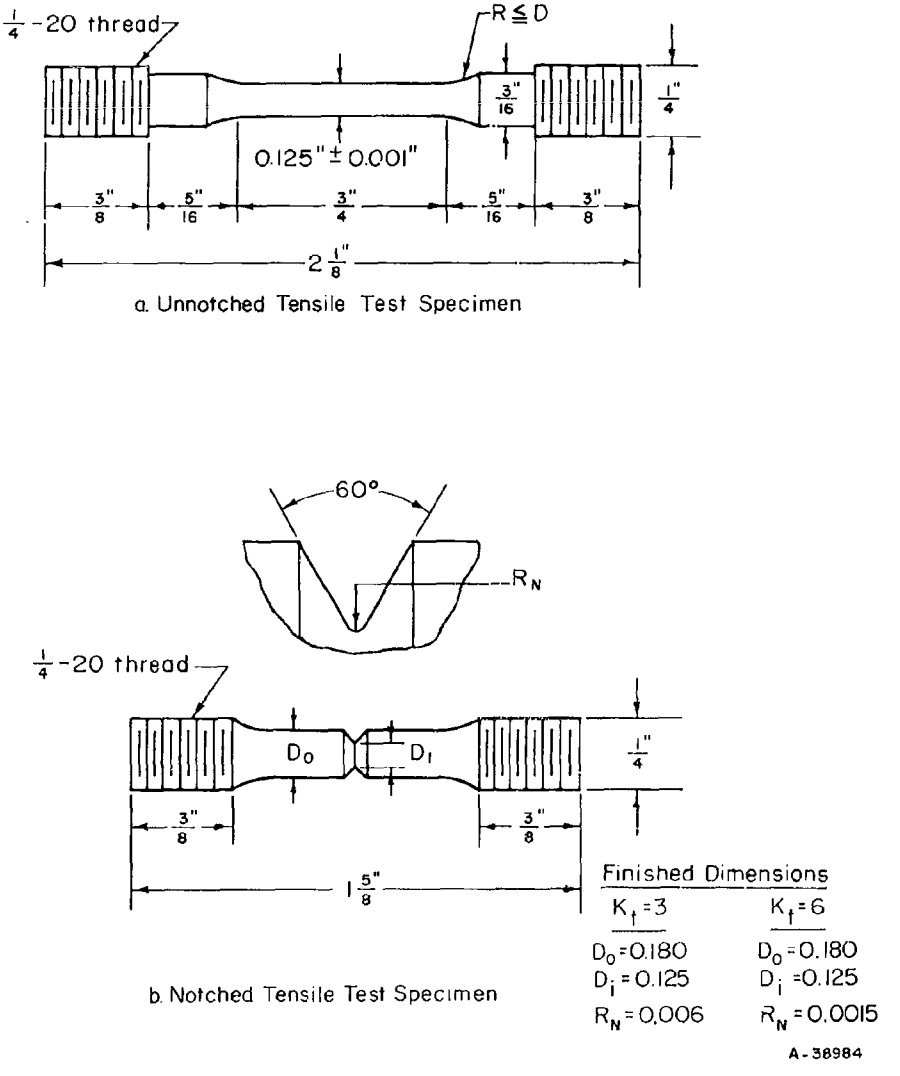


FIGURE A-85. UNNOTCHED AND NOTCHED BAR-TENSILE TEST SPECIMENS USED TO OBTAIN DATA SHOWN IN FIGURE A-86

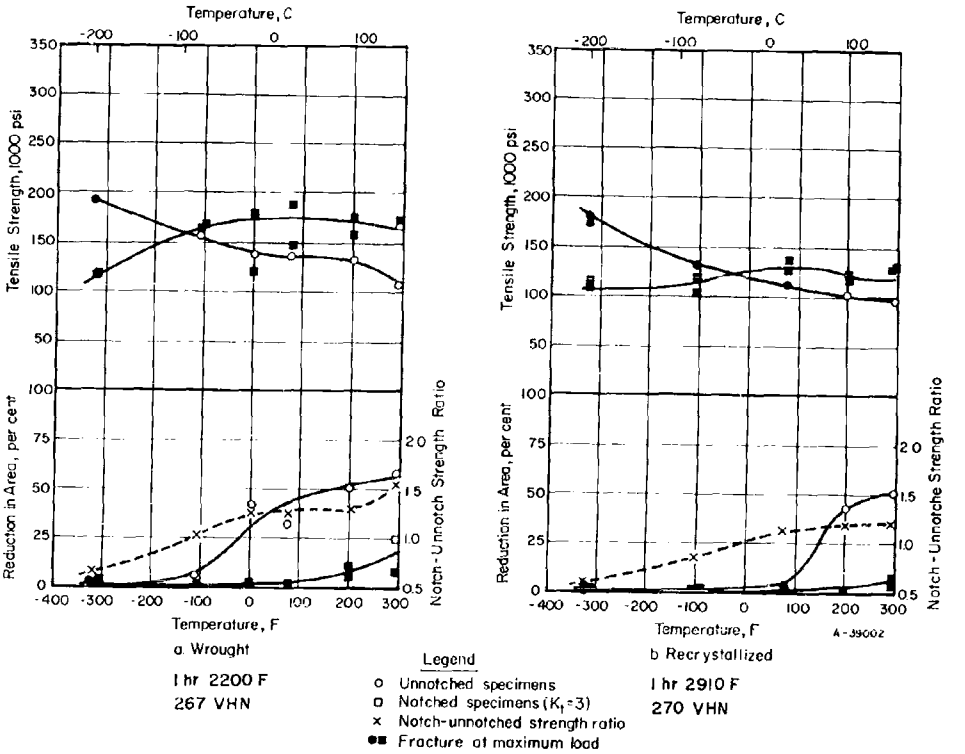


FIGURE A-86. TENSILE PROPERTIES FOR WROUGHT AND RECRYSTALLIZED ARC-MELTED F-48[5]

	Unnotched	Notched
Crosshead Speed, in./min	0.02	0.005

Analyses: 15-16% W, 5.0-5.2% Mo, 1.0-1.4% Zr, 0.0200-0.0400% C, 0.0200-0.035% N, and 0.0200-0.0500% O.

TABLE A-115. STRESS-RUPTURE PROPERTIES OF UPSET FORGED AND ANNEALED F-48[a][6]

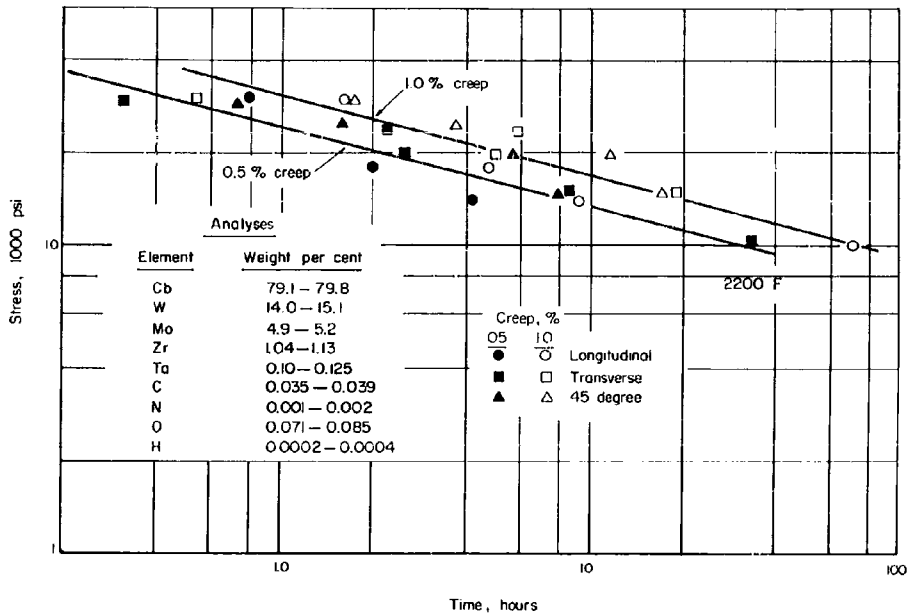
Temperature, F	Stress, 1000 psi	Rupture Life, hours	Elongation in 1/2 Inch, per cent	Reduction in Area, per cent
2000	60	0.4	26	74
	55	1.8	26	71
	44	14.1	28	81
2300	38	0.2	44	81
	28	4.1	66	86
	25	4.0	23	76
	24	12.1	44	78
2600	23	0.3	76	82
	17	1.2	94	86
	11	11.3	106	90

(a) Forged 75 per cent at 2500 F, annealed 1 hour at 2500 F.

TABLE A-116. RUPTURE STRENGTHS OF STRESS-RELIEVED F-48 SHEET (0.040 INCH)[a][3]

Temperature, F	Stress to Produce Rupture, 1000 psi		
	1 Hour	10 Hours	100 Hours
1600	65	63	60
2000	45	38	30
2100	35	31	25
2200	34	26	20
2500	18	13.5	9

(a) Stress relieved 1 hour at 2200 F. Data taken from Larson-Miller plot, Figure A-94.



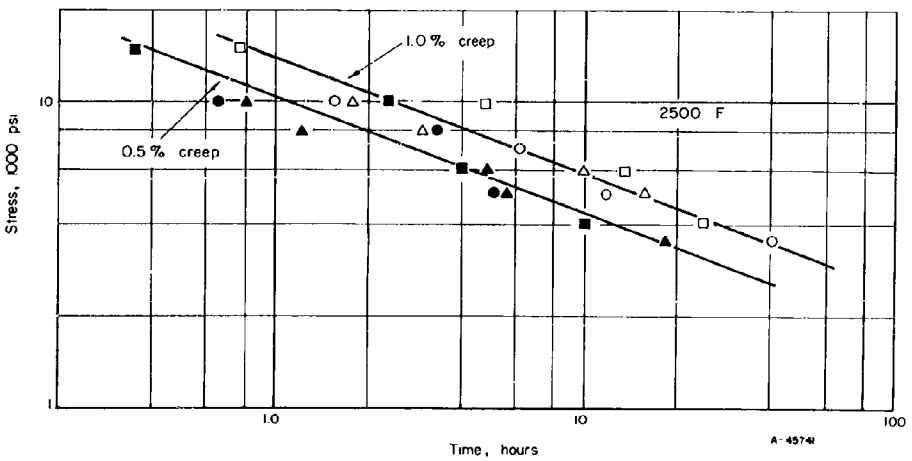


FIGURE A-87. CREEP BEHAVIOR OF D-40 PLATE AT 2200 F AND 2500 F[4]

Chemical analyses given in Table A-106.

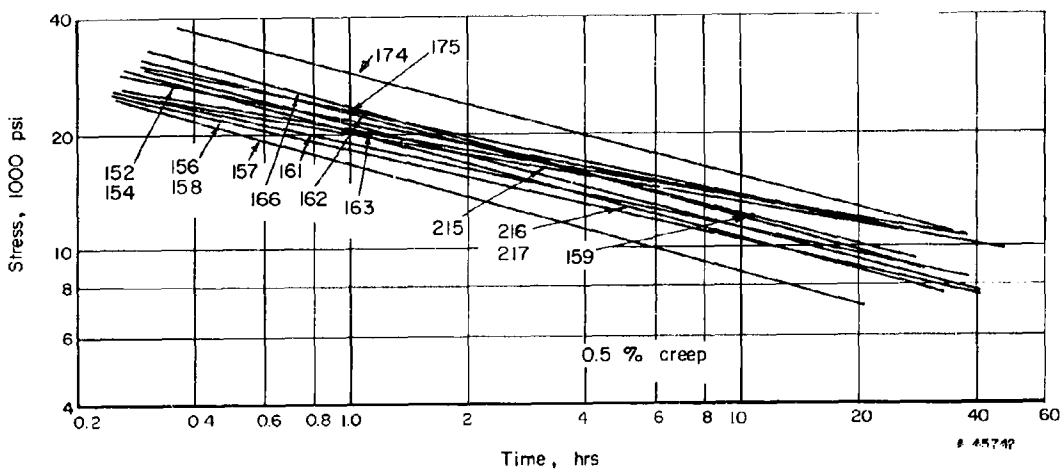


FIGURE A-88. CREEP BEHAVIOR OF SEVERAL HEATS OF D-40 PLATE AT 2200 F[4]

Chemical analyses given in Table A-106.

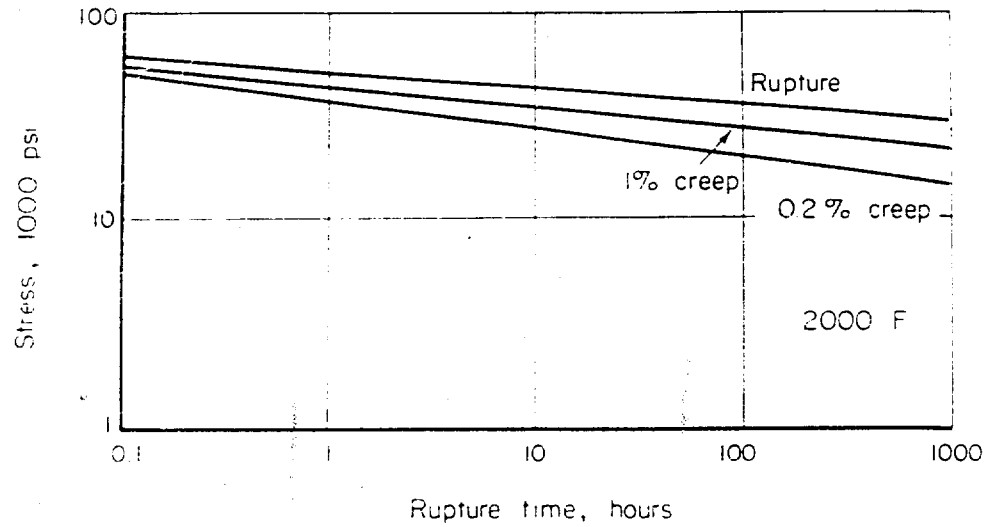


FIGURE A-89. CREEP AND STRESS-RUPTURE PROPERTIES OF EXTRUDED, SWAGED, AND STRESS-RELIEVED F-48 BAR STOCK(1)

Stress relieved 2000 F.
Bar stock 0.4-inch diameter.

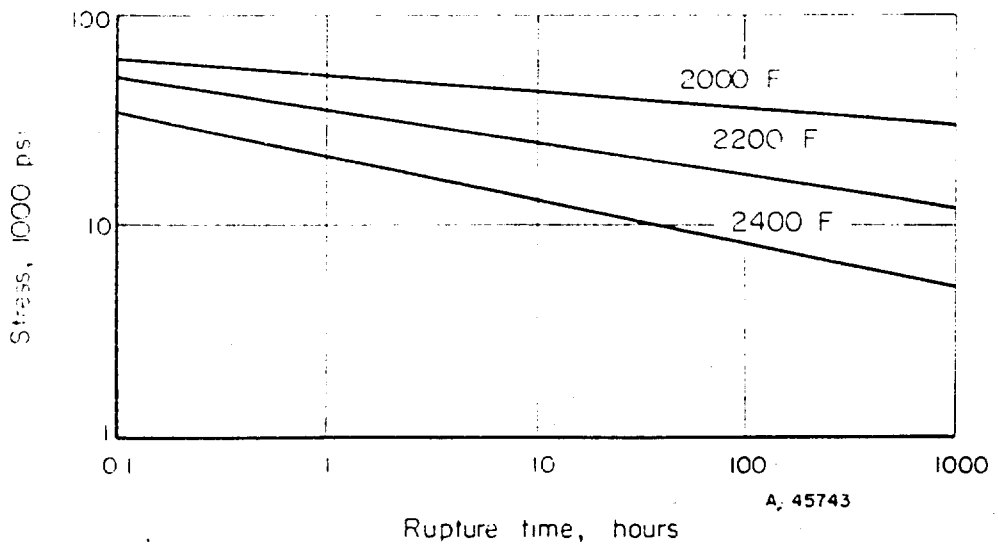


FIGURE A-90. STRESS-RUPTURE PROPERTIES OF EXTRUDED, SWAGED, AND STRESS-RELIEVED F-48 BAR STOCK(1)

Stress relieved 2000 F.
Bar stock 0.4-inch diameter.
Data at 2400 F estimated from Larson-Miller plot.

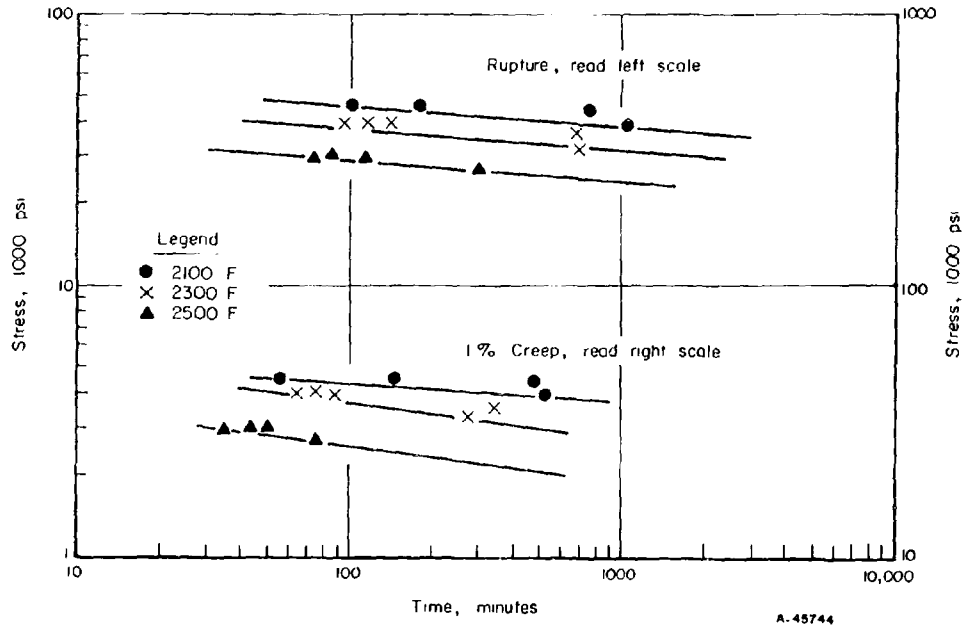


FIGURE A-91. CREEP AND STRESS-RUPTURE PROPERTIES OF COATED F-48 TESTED IN AIR AT 2100 TO 2500 F[2]

	Billet Chemistry					
	Weight Per Cent			PPM		
Location	W	Mo	Zr	C	O	N
Top	15.7	5.2	0.99	443	210	13
Bottom	15.3	5.2	1.10	320	150	57

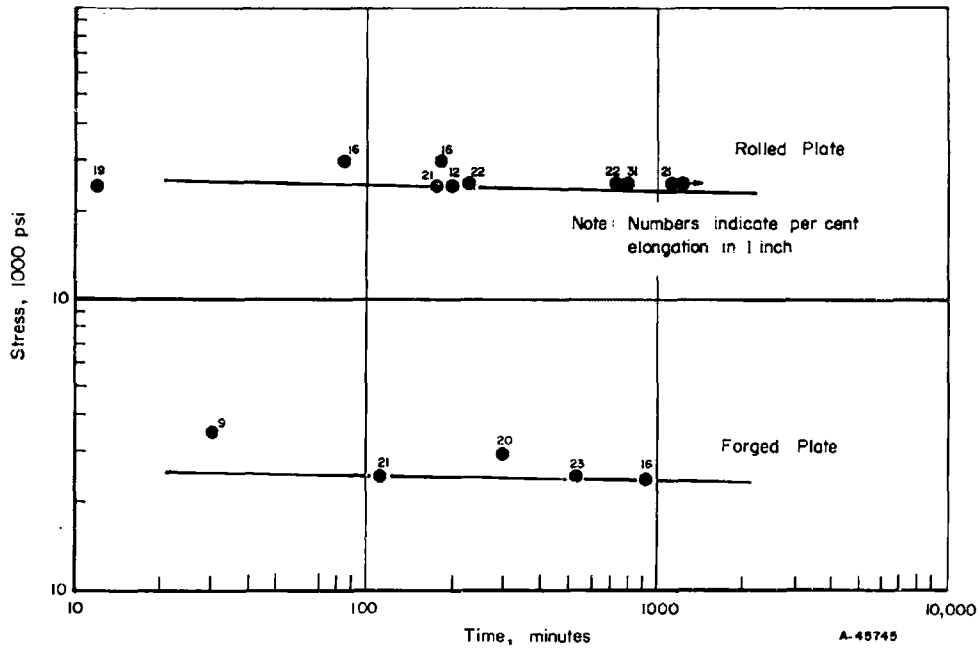
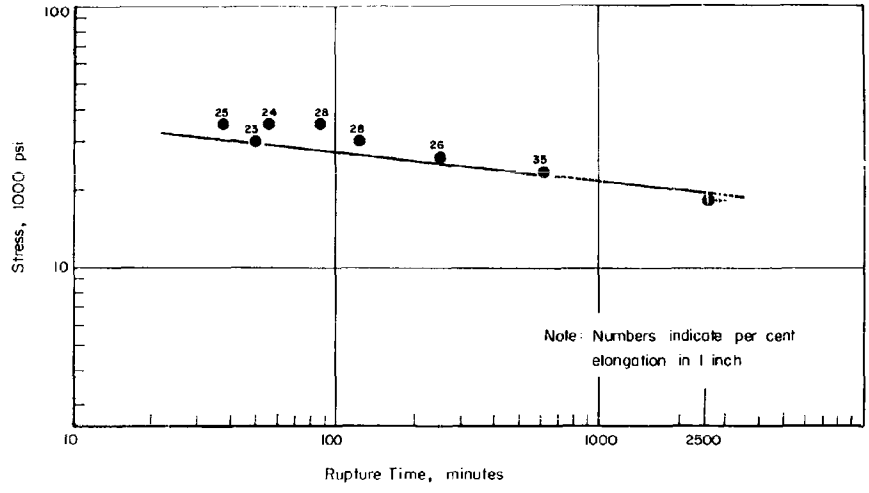
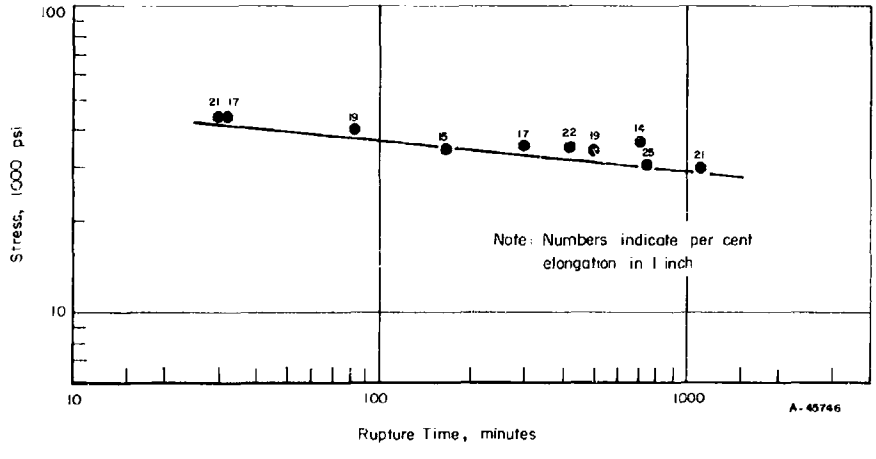


FIGURE A-92. STRESS-RUPTURE PROPERTIES OF F-48 PLATE AT 2300 F[2]

	Billet Chemistry					
	Weight Per Cent			PPM		
Location	W	Mo	Zr	C	O	N
Top	15.6	4.6	0.97	320	180	41
Bottom	15.7	4.8	0.99	430	270	85



	Weight Per Cent			PPM		
	W	Mo	Zr	C	O	N
Finished Plate	12.4	3.9	1.0	232	109	36



	Billet Chemistry					
	Weight Per Cent			PPM		
Location	W	Mo	Zr	C	O	N
Top	13.8	4.7	0.92	290	210	17
Bottom	14.5	4.8	0.98	330	190	37

FIGURE A-93. STRESS-RUPTURE PROPERTIES OF F-48 AT 2300 F[2]

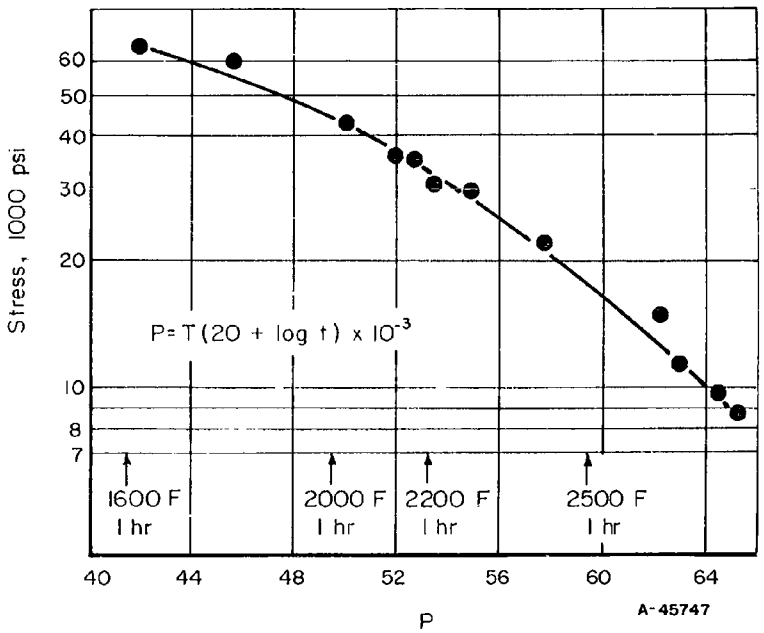


FIGURE A-94. STRESS-RUPTURE CHARACTERISTICS OF STRESS-RELIEVED F-48 SHEET (0.040 INCH)[3]

Stress relieved 1 hour at 2200 F.

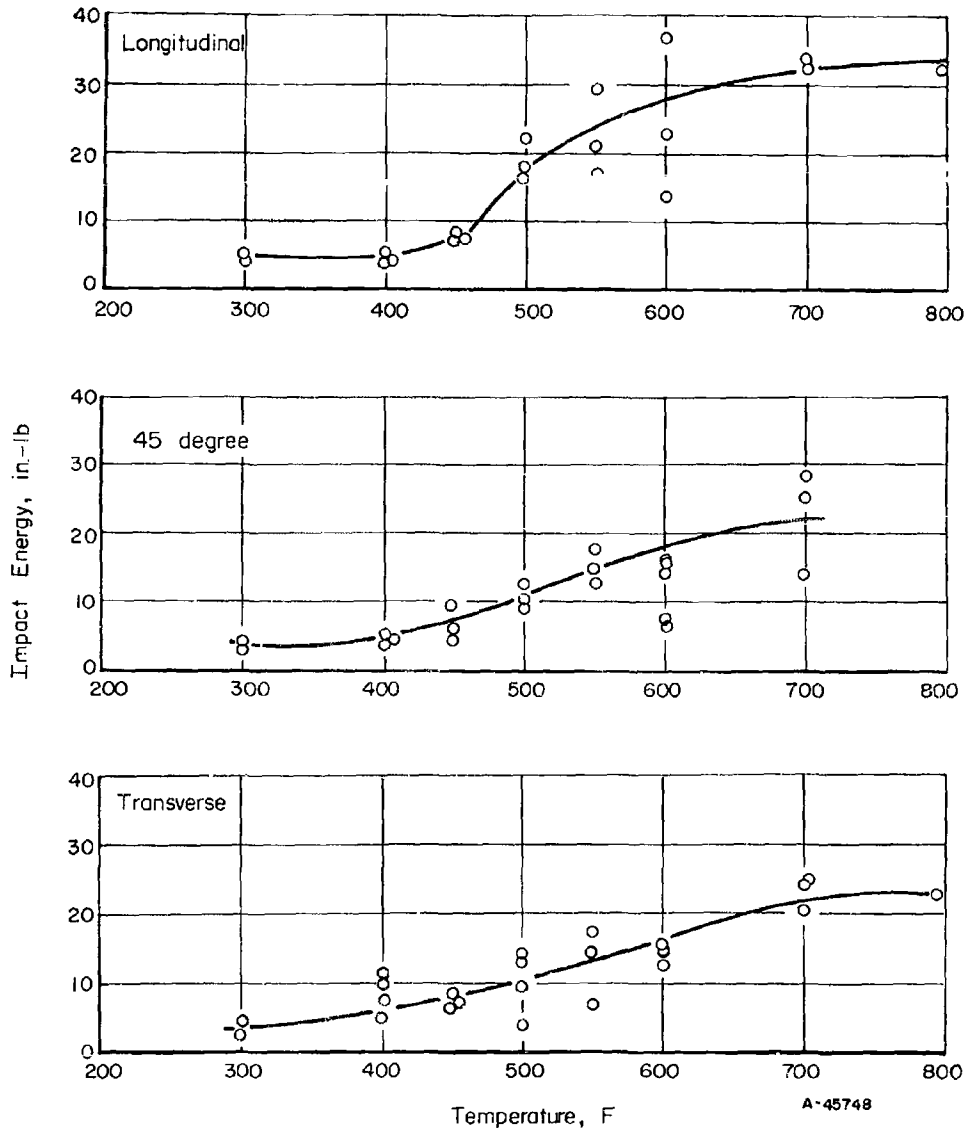


FIGURE A-95. IMPACT RESISTANCE OF D-40 IN THE LONGITUDINAL, TRANSVERSE, AND 45-DEGREE DIRECTIONS[4]

Analyses 79.1-79.8% Cb, 14.0-15.1% W, 4.9-5.2% Mo, 1.04-1.18% Zr, 0.10-0.125% Ta, 0.035-0.039% C, 0.001-0.002% N, 0.071-0.085% O, and 0.0002-0.0004% H.

TABLE A-117. SHEAR STRENGTH OF STRESS-RELIEVED F-48 SHEET (0.040 INCH) FROM ROOM TEMPERATURE TO 2500 F[a][3]

Temperature, F	Shear Strength, 1000 psi	Shear Strength/ Tensile Strength Ratio
RT	75.6	0.64
	78.2	
1600	43.8	0.55
	42.7	
2200	37.8	0.71
	34.6	
2500	21.6	0.66
	23.4	

(a) Stress relieved 1 hour at 2200 F.

TABLE A-118. BEARING STRENGTH OF STRESS-RELIEVED F-48 SHEET (0.035 INCH) FROM ROOM TEMPERATURE TO 2500 F[a][3]

Test Direction	Temperature, F	Bearing Strength, 1000 psi	Bearing Strength/ Tensile Strength Ratio	Bearing, Yield Strength, 1000 psi	Bearing Yield Strength/ Yield Strength Ratio
		Edge Distance 0.375 Inch (1.5d)			
RT	Longitudinal	180.0	1.5	154.6	1.5
		194.0	1.6	163.4	1.6
RT	Transverse	163.0	--	142.4	--
		177.0	--	145.8	--
RT	45 Degree	186.2	--	145.0	--
		214.0	--	152.0	--
1600	Longitudinal	158.5	1.9	114.2	1.6
		152.2	1.8	103.0	1.4
2500	Longitudinal	76.6	2.3	55.3	1.8
		76.2	2.3	55.0	1.8
		Edge Distance 0.500 Inch (2.0d)			
RT	Longitudinal	163.5	1.3	148.3	1.4
		162.0	1.3	145.0	1.4
RT	Transverse	193.5	--	148.1	--
		203.0	--	164.0	--
2500	Longitudinal	73.5	2.2	63.4	2.1
		78.4	2.4	63.2	2.1

(a) Stress relieved 1 hour at 2200 F.

4. Metallurgical Properties

a. Fabricability: extrusion (4:1) temperatures in the range 2800 to 3200 F have proved satisfactory; intermediate conversion steps depend to a great extent on the specific equipment used; rough finishing temperatures for mill products should be in the range 1800 to 2000 F with furnace temperatures at 2000 to 2400 F; final passes may be performed at lower temperatures[1]

b. Transition temperature: <-40 F for stress-relieved (1 hour at 2200 F) sheet (0.040 inch)[3]

d. Stress-relief temperature: 1 hour at 2200 F for bar and sheet[3,5]

e. Recrystallization temperature: effect of annealing temperature on recrystallization and hardness of extrusions and sheet

Temperature, F	Recrystallization, per cent	Hardness, VHN
	Extrusions[6]	
As extruded	0	291
2500	2	274
2600	20	272
2700	70	267
	Sheet[3]	
As received[a]	0	275
2400[b]	25	255
2600	70	245
2700	75	245
2800	80	248
3000	95	275
3500	100	305

(a) Stress relieved 1 hour at 2200 F.
(b) All exposures for 1 hour.

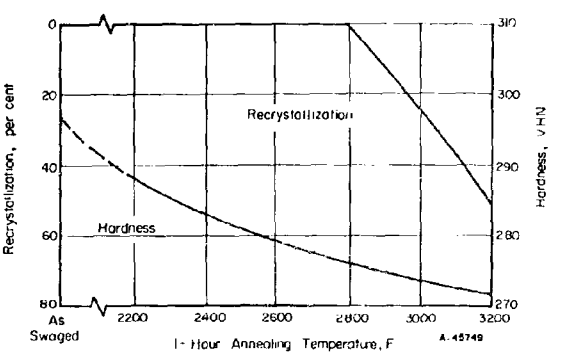


FIGURE A-96. RECRYSTALLIZATION BEHAVIOR OF EXTRUDED (~4:1) AND SWAGED (~85 PER CENT) F-48 BAR[1]

References

(1) "Recent Advances in Columbium Alloys", Applied Research Operation, Flight Propulsion Laboratory Department, General Electric Co. (July, 1959).

(2) Cox, J. W., and Werner, R. W., "Engineering Testing of the F-48 Columbium Alloy", University of California, Lawrence Radiation Laboratory Contract No. W-7405-eng-48, UCRL-6187 Rev. (August 2, 1961).

(3) Neff, C. W., Frank, R. G., and Tuft, L., "Refractory Metals Structural Development Program", Refractory Alloy and Coating Development, Volume II, McDonnell Aircraft Corp. and General Electric Co., ASD TR 61-392 (October, 1961).

(4) Unpublished data obtained at Battelle Memorial Institute for University of California, Lawrence Radiation Laboratory, under Contract No. W-7405-eng-92 (1963).

(5) Imgram, A. G., et al., "Notch Sensitivity of Refractory Metals", Battelle Memorial Institute, ASD TR 61-474 (August, 1961).

(6) Carson, R. O., "The Development of Optimum Manufacturing Methods for Columbium Alloy Forgings", Crucible Steel Co. of America, Contract No. AF 33(600)-39944, ASD Interim Report 7-782 (V) (August, 1961).

(7) Ogden, H. R., "Department of Defense Refractory Metals Sheet-Rolling Program", Status Report No. 2, Battelle Memorial Institute, DMIC Report 176 (October 15, 1962).

(8) "Shear Strength Properties of Refractory Metal Fasteners", McDonnell Aircraft Corp., Contract No. AF 33(657)-7749 and BPSN:2(8-7381)-73812, Report 9346, Serial No. 3 (January 10, 1963).

Cb-15W-5Mo-5Ti-1Zr

1. Identification of Material

   a. Designation: F-50 (General Electric)

   b. Chemical composition: nominal analyses[1]

Element	Weight Per Cent
W	15
Mo	5
Ti	5
Zr	1
C	0.04-0.08
O	0.03-0.06

   c. Forms available: ingot and fabricated shapes on a best efforts basis

2. Physical Properties

   a. Melting point: 4400 (estimated)[1]

   b. Density: 0.33 lb/in.^{3}[1]

   c. Thermal expansion: linear coefficient is estimated to be 5.0×10^{-6}/F (75-2100 F)[1]

   d. Thermal conductivity: estimated to be 20 Btu/(ft^2)(hr)(F/ft) at 75 F[1]

3. Mechanical Properties

   a. Tensile Properties at Room Temperature

      Ultimate tensile strength: 123,000 psi for extruded, swaged, and stress-relieved bar stock[1]

      Tensile yield strength: 80,000 (0.2 per cent offset) for extruded, swaged, and stress-relieved bar stock[1]

      Elongation: 25 per cent for extruded, swaged, and stress-relieved bar stock[1]

      Modulus of elasticity: 24×10^6 psi[1]

b. Effect of Temperature on Tensile Properties

Ultimate tensile strength: Figure A-97

Tensile yield strength: Figure A-97

Elongation: Figure A-97

Modulus of elasticity: Figure A-98

c. Creep and Stress-Rupture Properties

Figure A-99

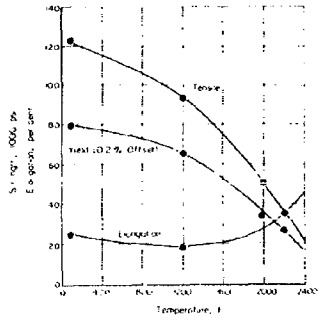


FIGURE A-97. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF EXTRUDED, SWAGED, AND STRESS-RELIEVED F-50 BAR STOCK[1]

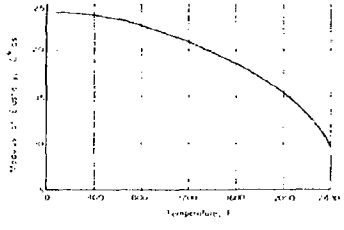


FIGURE A-98. EFFECT OF TEMPERATURE ON THE MODULUS OF ELASTICITY OF F-50[1]

Data from stress-strain measurements.

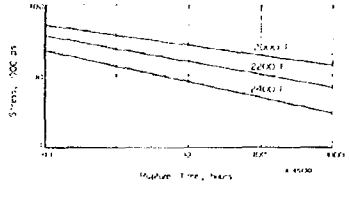


FIGURE A-99. STRESS-RUPTURE PROPERTIES OF EXTRUDED, SWAGED, AND STRESS-RELIEVED F-50 BAR STOCK[1]

Stress relieved 2000 F.
Bar Stock 0.4-inch diameter.
Data at 2400 F estimated from Larson-Miller plot.

4. Metallurgical Properties

a. Fabricability: extrusion (4:1) temperatures in the range 2800 to 3200 F have proved satisfactory; intermediate conversion steps depend to a great extent on the specific equipment used; rough finishing temperatures for mill products should be in the range 1800 to 2000 F with furnace temperatures at 2000 to 2400 F; final passes may be performed at lower temperatures[1]

b. Transition temperature: slightly below RT

c. Stress-relief temperature: 1 hour at 2000 to 2200 F for extruded and swaged bar[1]

d. Recrystallization temperature: Figure A-100

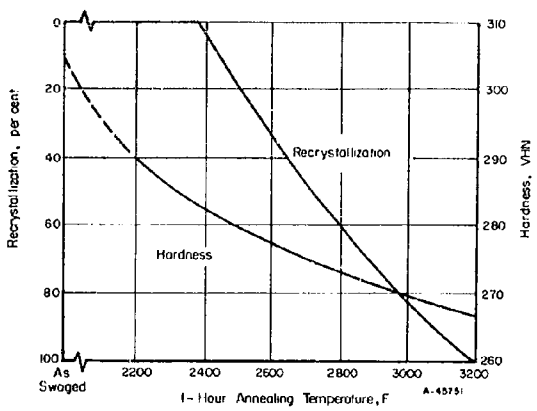


FIGURE A-100. RECRYSTALLIZATION BEHAVIOR OF EXTRUDED (~4:1) AND SWAGED (~85 PER CENT) F-50 BAR[1]

Reference

(1) "Recent Advances in Columbium Alloys", Applied Research Operation, Flight Propulsion Laboratory Department, General Electric Co. (July, 1959).

Cb-20W-1Zr

1. Identification of Material

   a. Designation: AS-30 (General Electric)

   b. Chemical composition: nominal analyses[1]

Element	Weight Per Cent
W	19-21
Zr	0.8-1.0
C	0.08-0.10
O	0.03 max.
N	0.03 max.
Cb	Balance

   c. Forms available: ingot and fabricated shapes on a best efforts basis

2. Physical Properties

   a. Density: 0.347 lb/in.^{3} (calculated)

3. Mechanical Properties

   a. Tensile Properties at Room Temperature

      Ultimate tensile strength: Table A-119

      Tensile yield strength: Table A-119

      Elongation: Table A-119

      Reduction in area: Table A-119

   b. Effect of Temperature on Tensile Properties

      Ultimate tensile strength: Table A-120

      Tensile yield strength: Table A-120

      Elongation: Table A-120

      Reduction in area: Table A-120

   c. Creep and Stress-Rupture Properties

Figure A-101

TABLE A-119. ROOM-TEMPERATURE TENSILE PROPERTIES OF STRESS-RELIEVED AS-30[a][1]

Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent
171.5	143.0	21	60

(a) Stress relieved at 2000 F after 90 per cent warm work. Test rate 0.005 inch per inch per minute. Analyses 19.3% W, 0.90% Zr, 0.0950% C, 0.0120% O, 0.0290% N, and 0.0001% H.

TABLE A-120. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF STRESS-RELIEVED AS-30[a][1]

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent
RT	171.5	143.0	21	60
1600	101.3	92.2	12	68
2000	85.0	81.1	13	75
2200	71.9	67.1	17	87

(a) Stress relieved at 2000 F after 90 per cent warm work. Test rate 0.005 inch per inch per minute. Analyses 19.3% W, 0.90% Zr, 0.0950% C, 0.0120% O, 0.0290% N, and 0.0001% H.

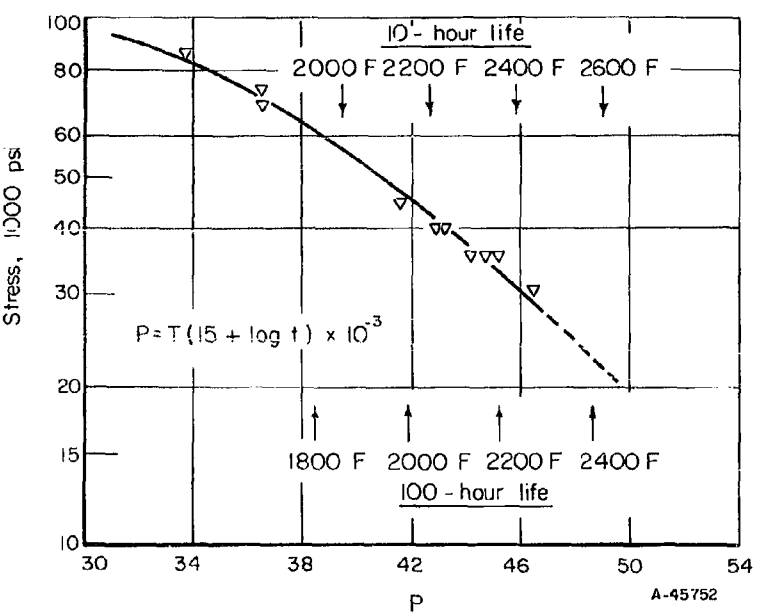


FIGURE A-101. STRESS-RUPTURE PROPERTIES OF AS-30[1]

Analyses 19.3% W, 0.96% Zr, 0.0950% C, 0.0120% O, 0.0290% N, and 0.0001% H.

4. Metallurgical Properties

   a. Fabricability: extrusion temperatures range from 2500 to 3000 F depending upon the reduction ratio desired; following extrusion, standard techniques for rolling or forging bar or sheet can be employed; processing temperatures should be kept high enough to avoid excessive cold working, but sufficiently low to take full advantage of carbide precipitation during secondary working.[1]

   b. Transition temperature: <RT[1]

   c. Stress-relief temperature: 1 hour at 2000 F for material warm worked 90 per cent[1]

Reference

(1) "Recent General Electric Company Developments in Columbium-Base Alloys", Materials and Processes, Applied Research Operation, Flight Propulsion Laboratory Department, General Electric Co. (February, 1962).

Cb-20W-10Ti-6Mo

1. Identification of Material

   a. Designation: D-41 (Du Pont)

   b. Chemical composition: Table A-121

   c. Forms available: ingot and fabricated shapes on a best efforts basis

TABLE A-121. CHEMICAL ANALYSIS OF ARC-MELTED D-41 INGOT AS DETERMINED BY FOUR LABORATORIES[1]

Laboratory	Value[a]	Weight Per Cent				PPM		
		W	Mo	Ti	C	O	N	H
1	$\bar{X}$	21.07	6.44	8.87	.0870	112	47	2
	R	.05	.03	0.29	0.140	22	8	0
	N	3	3	3	2	2	2	2
2	$\bar{X}$	20.48	6.35	9.05	.087	170	35	5.4
	R	--	--	--	--	--	--	--
	N	1	1	1	1	1	1	1
3	$\bar{X}$	20.96	6.55	9.15	.083	150	86	15
	R	0.25	.09	.06	.060	20	3	2
	N	3	3	3	2	2	2	2
3	$\bar{X}$	21.39	6.37	9.04	--	--	21	--
	R	0.85	0.30	0.52	--	--	3	--
	N	10	10	10	--	--	2	--
4	$\bar{X}$	20.77	7.05	9.00	.09	260	40	4
	R	0.15	.03	--	0	--	--	--
	N	2	2	1	2	1	1	1
4	$\bar{X}$	20.8	--	9.0	--	160	--	--
	R	--	--	--	--	40	--	--
	N	1	--	1	--	3	--	--

(a) X = arithmetic mean
R = range
N = number of determinations

2. Physical Properties

   a. Density: 0.32 lb/in.^{3}

3. Mechanical Properties

   a. Tensile Properties at Room Temperature

      Ultimate tensile strength: Tables A-122 and A-123

      Tensile yield strength: Table A-123

      Elongation: Tables A-122 and A-123

      Reduction in area: Table A-123

   b. Effect of Temperature on Tensile Properties

      Ultimate tensile strength: Tables A-123 and A-125

      Tensile yield strength: Tables A-124 and A-125

      Elongation: Tables A-124 and A-125

      Reduction in area: Tables A-124 and A-125

   c. Creep and Stress-Rupture Properties

      Tables A-126 and A-127

TABLE A-122. ROOM-TEMPERATURE TENSILE PROPERTIES OF D-41 EXTRUSIONS

Condition	Tensile Strength, 1000 psi	Elongation, per cent	Reference
As extruded (4:1)[a]	125	10	(3)
As extruded (6:1)[b]	136	--	(3)
Extruded, 1 hr 2700 F	119.3(T)	--	(1)

(a) Test rate 0.05 inch per inch per minute.
(b) Test rate 0.067 inch per inch per minute.

TABLE A-123. ROOM-TEMPERATURE TENSILE PROPERTIES OF ANNEALED D-41 UPSET FORGINGS[a][1]

Forging Temperature, F	Upset Reduction, per cent	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent
2300	52	124.0	--	Broke into 4 pieces	
2500	54	133.1	124.5	Broke into 3 pieces	
2700[b]	48	123.1	--	Broke into 3 pieces	
2300	72	134.2	126.4	3	3
2500	72	132.6	125.5	4	3
2700[b]	71	112.5	--	Broke into 3 pieces	

(a) Annealed 1 hour at 2500 F.
(b) Annealed 1/2 hour at 1400 F prior to testing.

TABLE A-124. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF D-41 EXTRUSIONS[3]

Temperature, F	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent	Reduction in Area, per cent
		As Extruded (4:1)[a]		
RT	125	--	--	--
2000	56.5	53.0	26	57
		As Extruded (6:1)[b]		
RT	136	--	--	--
200	122	--	--	--
400	107	--	--	--
600	88	--	--	--
800	88	--	--	--
1000	82.5	--	--	--
1200	82.5	--	--	--
1400	73.5	--	--	--
1600	68	--	--	--
1800	59.5	--	--	--
2000	45	--	--	--
		Extruded (6:1), Recrystallized 1 Hour at 2400 F[b]		
400	99	95	10	10
600	87.5	78	28.5	62
800	81	69	23	69
1000	85	65	21	67
1200	81	61.5	20	58
1400	81	61.5	17.5	54
1600	72	57	15	37
1800	53.5	48	11	28
2000	49	45.5	15	19

(a) Test rate 0.05 inch per inch per minute.
(b) Test rate 0.067 inch per inch per minute.

TABLE A-125. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF UPSET FORGED AND ANNEALED D-41[a][1]

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent
1000	94.0	70.0	20	63
2000	45.6	--	16	24
2300	25.0	--	13	21
2600	21.4	--	30	30

(a) Forged 75 per cent at 2500 F, annealed 1 hour at 2500 F.

TABLE A-126. STRESS-RUPTURE PROPERTIES OF UPSET FORGED AND ANNEALED D-41[a][1]

Temperature, F	Stress, 1000 psi	Rupture Life, hours	Elongation in 1/2 Inch, per cent	Reduction in Area, per cent
2000	33	0.3	12	14
	29	0.3	18	17
	25	0.8	15	18
	17	13.0	16	17
2300	24	0.1	8	24
	18	0.8	20	29
	12	6.4	20	34
2600	12	0.2	25	25
	9	0.7	32	23
	6	3.8	36	36

(a) Forged 75 per cent at 2500 F, annealed 1 hour at 2500 F.

TABLE A-127. STRESS-RUPTURE PROPERTIES OF D-41 BAR TESTED IN VACUUM AND AIR AT 2000 F[3]

Stress, 1000 psi	Rupture Life, hour	Elongation, per cent
Extruded (8:1) and Swaged Bar Tested in Vacuum		
40	0.5	20
30	5.5	25
30	6.1	25
25	21.1	25
20	52.9	21
Extruded and Coated Bar Tested in Air[a]		
30	1.8	1.7
25	29	2.4
23	73	5.2
20	130	7.6
20	148	8.9

(a) Annealed 1 hour at 2000 F.

4. Metallurgical Properties

a. Fabricability: can be extruded, forged, and swaged at temperatures above the recrystallization temperature; large forging reductions are readily possible at 2500 F[1]

b. Transition temperature: ~RT for extrusions and forgings[1,3]

c. Recrystallization temperature: 1 hour at 2400 F[3], 1 hour at 2500 F[2]; effect of annealing temperature on recrystallization and hardness of extrusion given below[1]

Temperature, F	Recrystallization, per cent	Hardness, VHN
As extruded	0	326
2400	30	316
2500	60	313
2600	90	269
2700	100	323

References

(1) Carsen, R. O., "The Development of Optimum Manufacturing Methods For Columbium Alloy Forgings", Crucible Steel Co. of America, Contract No. AF 33(600)-39944, ASD Interim Report 7-782 (V) (August, 1961).

(2) Maykuth, L. J., and Ogden, H. R., "What Refractory Metal Shall I Use.... For Ultrahigh-Temperature Applications (Above 1800°F.)?", Metal Progress (October, 1961).

(3) Dana, A. W., et al., "Columbium and Columbium Alloy Extrusion Program", E. I. du Pont de Nemours and Co., Inc., Contract No. AF 33(600)-40700, Interim Report 1 (June 30, 1960).

Cb-5V-5Mo-1Zr

1. Identification of Material

   a. Designation: B-66 (Westinghouse)

   b. Chemical composition: Typical analyses are given below[1]

Element	Composition, weight per cent Range	Nominal
V	4.5-5.5	5.0
Mo	4.5-5.5	5.0
Zr	0.85-1.3	1.0
O	0.030 max	0.012
N	0.020 max	0.006
C	0.020 max	0.006
Cb	Remainder	Remainder

   c. Forms available: plate, sheet, strip, foil, bar, wire, forgings, and extrusions[1]

2. Physical Properties

   a. Melting point: 4300 F[1]

   b. Density: 0.305 lb/in.^{3}

   c. Thermal expansion: Table A-128

   d. Electrical resistivity: 10.9 microhm-cm at -320 F; 22.0 microhm-cm at RT; and 24.9 microhm-cm at 210 F[1]

TABLE A-128. COEFFICIENT OF THERMAL EXPANSION OF B-66[1]

Temperature C	Temperature F	Coefficient of Thermal Expansion 10^{-6} In./In./C	Coefficient of Thermal Expansion 10^{-6} In./In./F
25-260	80-500	7.24	4.02
25-540	80-1000	7.42	4.12
25-815	80-1500	7.70	4.27
25-1095	80-2000	8.15	4.52
25-1365	80-2500	8.52	4.73
25-1650	80-3000	8.77	4.87
25-1925	80-3500	8.94	4.96

3. Mechanical Properties

a. Tensile Properties at Room Temperature

Ultimate tensile strength: Tables A-129 through A-132

Tensile yield strength: Tables A-129 through A-132

Elongation: Tables A-129 through A-132

Reduction in area: Tables A-129 through A-130

Modulus of elasticity: 14.8×10^6 psi[2]
15.31×10^6 psi[1]
Table A-132

b. Effect of Temperature on Tensile Properties

Ultimate tensile strength: Tables A-133 through A-137

Tensile yield strength: Tables A-133 through A-137

Elongation: Tables A-133 through A-137

Reduction in area: Table A-133

Modulus of elasticity: Tables A-137 and A-138

c. Creep and Stress-Rupture Properties

Table A-139
Figure A-102

d. Other Selected Mechanical Properties

Hardness: for various conditions see below[1]

Condition	Vickers, DPH	Rockwell B	Rockwell C
As rolled	325	--	35
Stress relieved 1 hr 2000 F	260	--	20
Recrystallized 1 hr 2500 F	230	90	--

Bend ductility: for stress-relieved (1 hour 2000 F) sheet[1]

Temperature, F	Minimum Bend Radius, T
80	1
-320	1

TABLE A-129. SOME SELECTED ROOM-TEMPERATURE TENSILE PROPERTIES OF B-66

Condition	Tensile Strength, 1000 psi	Yield Strength (02.% Offset), 1000 psi	Elongation, per cent	Reduction in Area, per cent	Reference
Stress-relieved material (1 hr 1800-2000 F)[a]	115.5	95.0	20	--	(2)
Recrystallized material (1 hr 2500 F)[a]	101.5	76.5	26	--	(3)
Recrystallized material (1 hr 2500 F)[b]	107.0	85.6	23	--	(2)
Sheet (0.040 inch)[c]	99	74	24	--	(4)
Extruded, forged, and stress-relieved material (1 hr 2000 F)	111.4	87.6	31.4	65.6	(5)
Extruded, forged, and recrystallized material (1 hr 3270 F)	113.4	77.25	16.6	14.3	(5)

(a) Test rate 0.05 inch per inch per minute.
(b) Test rate 0.005 inch per inch per minute through 0.6 per cent yield, then 0.05 inch per inch per minute to fracture.
(c) Test rate 0.05 inch per minute crosshead speed.

TABLE A-130. ROOM-TEMPERATURE TENSILE PROPERTIES OF B-66 EXTRUDED TUBE BLANKS[a][6]

Condition	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 4D, per cent	Reduction in Area, per cent
As extruded	109.2	84.5	23	45
	109.6	86.3	28	51
Annealed 1 hr 2200 F	98.5	77.3	30	71
	100.8	78.9	30	79
Annealed 2 hr 2600 F	93.8	74.3	30	72
	94.6	75.7	34	70

(a) Test rate 0.005 inch per inch per minute to yield, then 0.05 inch per inch per minute to failure.

TABLE A-131. ROOM-TEMPERATURE TENSILE PROPERTIES OF B-66 REROLL FOIL STOCK AND FINISHED FOIL[a][7]

Coil Identification	Gage, inch	Recrystallization, per cent	ASTM Grain Size	Test Direction	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 2 Inches, per cent
			Reroll Foil Stock				
66-2, -3	0.050	90	7.5	L	109.1	77.8	26.5
				T	112.5	82.0	21.2
66-4	0.050	100	7.5	L	100.1	75.1	20.7
				T	103.0	77.8	21.5
66-5, -6	0.050	70	9.5	L	109.5	87.3	17.7
				T	111.3	89.7	13.0
			Finished Foil				
66-6	0.010	100	8.5	L	108.6	82.0	21.2
				T	110.5	80.1	24.0
66-2	0.006	100	9.0	L	100.0	76.5	22.5
				T	105.0	79.0	23.5
66-3	0.006	100	9.0	L	103.3	77.4	22.0
				T	101.0	78.0	15.0
66-5	0.006	100	8.5	L	103.3	78.6	16.0
				T	108.4	79.5	21.7
				45 deg	110.5	86.2	27.5
66-5	0.002	100	8.5	L	132.0	109.5	19.7

(a) Test rate 0.005 inch per inch per minute to 0.2 per cent yield, then 0.05 inch per inch per minute to failure. Analyses are as follows:

Coil Identification	Gage, inch	Weight Per Cent			PPM			
		Mo	V	Zr	O	N	C	H
			Reroll Foil Stock					
66-2, -3	0.050	5.1	5.15	1.04	210	222	105	<5
66-4	0.050	5.1	5.1	1.1	300	112	120	<10
66-5, -6	0.050	5.1	4.7	1.0	160	138	105	<10
			Finished Foil					
66-6	0.010	--	--	--	285	174	135	<10
66-2	0.006	--	--	--	80	65	145	<10
66-3	0.006	--	--	--	120	39	70	<10
66-5	0.006	--	--	--	345	79	65	<10
66-5	0.002	--	--	--	250	139	250	<5

TABLE A-132. AVERAGE ROOM-TEMPERATURE TENSILE PROPERTIES OF B-66 FOIL[a][8]

Thickness, mils	Test Direction	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 Inches, per cent	Modulus of Elasticity, 10^6 psi
2	L	126.1	107.3	15.1	14.2
6	L	105.0	84.7	21.5	15.9
6	T	104.9	84.3	23.4	15.3
10	L	104.6	82.4	24.5	15.4

(a) Average of 5 tests. Test rate 0.004 inch per inch per minute to 0.6 per cent offset, then 0.04 inch per inch per minute to failure.

TABLE A-133. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF ARC-CAST, EXTRUDED, AND FORGED B-66[5]

Temperature, F	1-Hour Annealing Treatment, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation, per cent		Reduction in Area, per cent
				Uniform	Total	
75	2000	111.4	87.6	19.2	31.4	65.6
	3270	113.4	77.25	0	16.6	14.3
1800	2000	70.0	65.4	2.3	36.7	60.3
2000	2000	53.4	45.8	1.5	37.5	77.0
2200	2000	41.74	37.8	1.6	35.2	78.2
	3270	40.5	39.2	0.7	3.8	9.9
2400	2000	28.0	23.5	1.8	57.0	91.3
	3270	25.7	23.9	0.7	8.2	9.9

TABLE A-134. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF B-66 SHEET (0.040 INCH) AS DETERMINED BY TWO LABORATORIES[a][4]

Temperature, F	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent
	Westinghouse		
75	99	74	24
2000	52	44	30
2200	39	36	54
2400	26	26	67
2600	20	20	44
	Du Pont		
2000	50	40	30
2200	35.9	32.9	55
2400	25.4	25.4	74

(a) Test rate 0.05 inch per minute crosshead speed.

TABLE A-135. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF RECRYSTALLIZED B-66 IN ARGON TESTED AT A FAST STRAIN RATE[a][3]

Temperature, F	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 1 Inch, per cent
2000	55.1	42.6	17.5
2200	44.4	38.2	21.0
2400	35.9	34.8	16.0
2600	25.9	29.3	31.0
2800	19.3	18.1	40.0

(a) Recrystallized 1 hour at 2500 F, approximately 50 microns of argon. Test rate 0.28 inch per inch per minute.

TABLE A-136. TYPICAL TENSILE PROPERTIES OF STRESS-RELIEVED AND RECRYSTALLIZED B-66[2]

Temperature, F	Tensile Strength, 1000 psi		Yield Strength (0.2% Offset), 1000 psi		Elongation in 1 Inch, per cent	
	0.05 In./In./Min Throughout	0.005 In./In./Min Through 0.6% Yield, Then 0.05 In./In./Min to Fracture	0.05 In./In./Min Throughout	0.005 In./In./Min Through 0.6% Yield, Then 0.05 In./In./Min to Fracture	0.05 In./In./Min Throughout	0.005 In./In./Min Through 0.6% Yield, Then 0.05 In./In./Min to Fracture
			Stress Relieved 1 Hour at 1800 to 2000 F			
-320	187.5	--	162.9	--	13	--
-200	149.8	--	127.2	--	27	--
RT	115.5	--	95.0	--	20	--
2000	48.5	--	42.6	--	41	--
2200 to 3000	Above recrystallization temperature, use data below					
			Recrystallized 1 Hour at 2500 F			
-320	195.6	--	154.4	--	7	--
-200	144.8	--	120.3	--	28	--
RT	102.0	107.0	77.0	85.6	33	23
500 to 1000	75.0	--	60.0	--	24	--
2000	52.0	46.2	42.5	39.7	32	48
2200	38.0	39.5	34.0	33.4	57	53
2400	26.1	--	26.0	--	87	--
2500	--	22.2	--	21.6	--	60
2600	21.0	--	20.0	--	55	--
2690	--	15.7	--	15.4	--	48
3000	--	9.4	--	8.4	--	40

TABLE A-137 EFFECT OF STRAIN RATE ON THE TENSILE PROPERTIES OF RECRYSTALLIZED B-66 IN ARGON TESTED AT 2000 F[a][2]

Strain Rate, in./in./min	Tensile Strength, 1000 psi	Yield Strength (0.2% Offset), 1000 psi	Elongation in 2 Inches, per cent	Modulus of Elasticity, 10^6 psi
.004	43.0	35.6	6.5	12.2
.026	44.1	33.0	5.0	12.1
.045	47.8	37.4	12.0	13.1
.200	56.9	42.3	17.0	14.8

(a) Recrystallized 1 hour at 2500 F, approximately 50 microns of argon.

TABLE A-138. EFFECT OF TEMPERATURE ON THE MODULUS OF ELASTICITY OF B-66[2]

Temperature, F	Modulus of Elasticity, 10^6 psi (a)	(b)
75	14.6	--
1800	--	--
2000	11.8	15.5
2200	--	13.5
2400	--	13.5
2500	7.8	--
2600	--	11.5
2690	4.6	--
2800	--	10.0
3000	4.8	--

(a) Test rate 0.005 inch per inch per minute through 0.2 per cent yield, then 0.05 inch per inch per minute to fracture.

(b) Test rate 0.24 inch per inch per minute.

TABLE A-139. CREEP AND STRESS-RUPTURE BEHAVIOR OF RECRYSTALLIZED B-66 SHEET (0.040 INCH) IN ARGON[a][2]

Temperature, F	Stress, psi	Secondary Creep Rate, [illegible]	Rupture Time Min	Rupture Time Sec
2000	48.4	0.133	0	24
	47.4	0.166	0	58
	45.2	0.067	0	48
	44.0	0.0087	7	29
	40.0	0.0051	4	56
	35.2	0.004	13	11
	34.2	0.0017	22	52
	29.2	0.00011	54	12
2200	37.3	0.071	2	38
	32.2	0.0398	2	17
	27.3	0.0049	6	4
	26.0	0.0043	21	10
	23.6	0.0017	26	44
	19.7	0.00098	27	56
2400	29.7	0.192	0	33
	25.9	0.036	1	25
	18.1	0.0038	37	54
	12.4	0.0014	52	20
	10.3	0.0011	46	40
	9.6	0.0006	61	51[b]
2600	21.4	0.237	0	18
	21.1	0.172	0	52
	17.6	0.039	2	41
	12.1	0.008	9	10
	7.0	0.0022	43	32
	3.7	0.0012	57	4[b]
2800	17.0	0.37	0	36
	15.3	0.16	1	18
	13.0	0.061	1	24
	6.6	0.015	15	10
	4.4	0.0046	30	30[b]
	1.7	0.0029	60	0[b]
3000	17.1	0.5	0	15
	15.2	0.35	0	16
	13.0	0.167	0	36
	8.6	0.105	0	54
	7.9	0.051	2	19
	4.6	0.021	9	42
	2.9	0.0122	9	27
	0.92	0.0012	29	8

(a) Recrystallized 1 hour at 2500 F, approximately 50 microns of argon.
(b) Test discontinued.

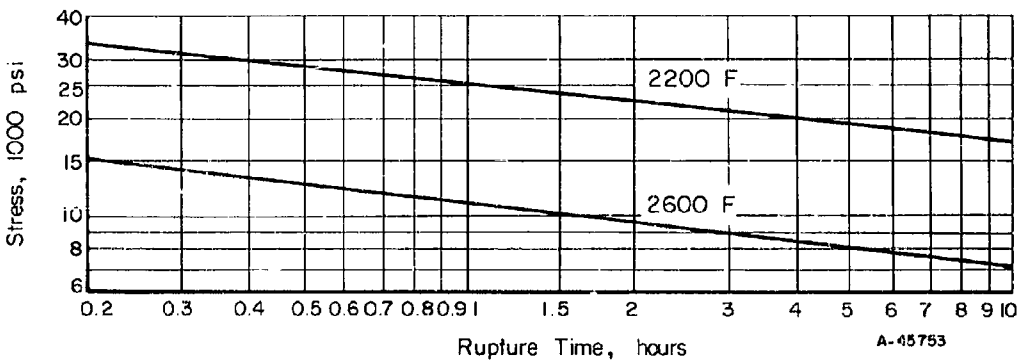


FIGURE A-102. STRESS-RUPTURE OF B-66 AT 2200 AND 2600 F[1]

Nominal analyses 5.0% V, 5.0% Mo, 1.0% Zr, 0.012% O, 0.006% N, and 0.006% C.

4. Metallurgical Properties

a. Fabricability: arc-cast ingots can be successfully extruded to sheet bar at 2500 to 3000 F; subsequent rolling to plate can be performed at 2010 to 2190 F[9]; highly formable alloy which can be punched, blanked, or sheared at room temperature without edge cracking; operations such as bending, brake forming, drawing and spinning can be performed at room temperature, although they can be accomplished with greater ease at slightly elevated temperatures[1]

b. Transition temperature: <-320 F[1]

c. Recrystallization temperature: Table A-140

TABLE A-140. RECRYSTALLIZATION BEHAVIOR OF B-66[2]

Annealing Temperature, F	35 to 40 Per Cent Cold Work		85 to 90 Per Cent Cold Work	
	Hardness, DPH	Recrystallization, per cent	Hardness, DPH	Recrystallization, per cent
RT	300-310	0	320-325	0
1800	--	--	275-280	5
2000	252	0	230	85-95
2200	249	5	228	95
2400	235	95	--	--
2500	--	--	228	100
2600	227	--	--	--

References

(1) "B-66 Columbium (Niobium) Base Alloy Refractory Metal", Westinghouse Electric Corp., Special Technical Data 52-364 (June, 1962).

(2) Personal communication with Westinghouse Electric Corp. (June, 1963).

(3) "B-66 Columbium (Niobium) Base Alloy Refractory Metal", Correction Sheet, Westinghouse Electric Corp., Special Technical Data 52-364 (November 1, 1962).

(4) Letter from J. R. Lane, National Academy of Sciences National Research Council, to members of the Alloy Requirements and Selection Subpanel Refractory Metals Sheet Rolling Panel (October 12, 1962).

(5) Begley, R. T., "Development of Niobium-Base Alloys", Westinghouse Electric Corp., WADC TR57-344, Part V (January, 1961).

(6) Clark, J. S., "Columbium Alloy Extrusion Program", E. I. du Pont de Nemours and Co., Inc., Contract No. AF 33(600)-40700, Phase V: Tubing Program, Interim Report VII (February, 1963).

(7) Personel communication with G. P. Trosi, Metals and Controls Inc., regarding "Development of Optimium Processing Parameters for Refractory Metal Foil", Contract No. AF 33(657)-9384 (June, 1963).

(8) Savage, C. H., and Root, D. C., "Determination of Mechanical and Thermophysical Properties of Coated Refractory and Superalloy Thin Sheet", North American Aviation, Inc., Contract No. AF 33(657)-9416, Third Progress Report, SID 62-1219-3 (April 15, 1963).

(9) Letter from R. T. Begley, Westinghouse Electric Corp., to R. I. Jaffee, Battelle Memorial Institute, regarding Columbium data presented to the Subpanel on Alloy Requirements and Selection of the MAB (February 27, 1961).

LIST OF DMIC TECHNICAL REPORTS ISSUED
DEFENSE METALS INFORMATION CENTER

Battelle Memorial Institute

Columbus 1, Ohio

Copies of the technical reports listed below may be obtained from DMIC [illegible] by Government [illegible], and by Government contractors, subcontractors, and their suppliers. Others may obtain copies from the Office of Technical Services, Department of Commerce, Washington 25, D. C. See PB numbers and prices in parentheses.

DMIC Report Number	Title
46D	Department of Defense Titanium Sheet-Rolling Program – Uniform Testing Procedure for Sheet Materials, September 12, 1958 (PB 121649 $1.25)
46E	Department of Defense Titanium Sheet-Rolling Program – Thermal Stability of the Titanium Sheet-Rolling-Program Alloys, November 26, 1958 (PB 151061 $1.25)
46F	Department of Defense Titanium Sheet-Rolling Program Status Report No. 4, March 20, 1959 (PB 151065 $2.25)
46G	Department of Defense Titanium Sheet-Rolling Program – Time-Temperature-Transformation Diagrams of the Titanium Sheet-Rolling Program Alloys, October 19, 1959 (PB 151075 $2.25)
46H	Department of Defense Titanium Sheet-Rolling Program, Status Report No. 5, June 1, 1960 (PB 151087 $2.00)
46I	Statistical Analysis of Tensile Properties of Heat-Treated Ti-4Al-3Mo-1V Sheet, September 15, 1960 (PB 151095 $1.25)
46J	Statistical Analysis of Tensile Properties of Heat-Treated Ti-4Al-3Mo-1V and Ti-2.5Al-16V Sheet, June 6, 1961 (AD 259284 $1.25)
106	Beryllium for Structural Applications, August 15, 1958 (PB 121648 $3.00)
107	Tensile Properties of Titanium Alloys at Low Temperature, January 15, 1959 (PB 151062 $1.25)
108	Welding and Brazing of Molybdenum, March 1, 1959 (PB 151063 $1.25)
109	Coatings for Protecting Molybdenum From Oxidation at Elevated Temperature, March 6, 1959 (PB 151064 $1.25)
110	The All-Beta Titanium Alloy (Ti-13V-11Cr-3Al), April 17, 1959 (PB 151066 $3.00)
111	The Physical Metallurgy of Precipitation-Hardenable Stainless Steels, April 20, 1959 (PB 151067 $2.00)
112	Physical and Mechanical Properties of Nine Commercial Precipitation-Hardenable Stainless Steels, May 1, 1959 (PB 151068 $3.25)
113	Properties of Certain Cold-Rolled Austenitic Stainless Sheet Steels, May 15, 1959 (PB 151069 $1.75)
114	Ductile-Brittle Transition in the Refractory Metals, June 25, 1959 (PB 151070 $2.00)
115	The Fabrication of Tungsten, August 14, 1959 (PB 151071 $1.75)
116R	Design Information on 5Cr-Mo-V Alloy Steels (H-11 and 5Cr-Mo-V Aircraft Steel) for Aircraft and Missiles (Revised), September 30, 1960 (PB 151072-R $1.50)
117	Titanium Alloys for High-Temperature Use Strengthened by Fibers or Dispersed Particles, August 31, 1959 (PB 151073 $2.00)
118	Welding of High-Strength Steels for Aircraft and Missile Applications, October 12, 1959 (PB 151074 $2.25)
119	Heat Treatment of High-Strength Steels for Aircraft Applications, November 27, 1959 (PB 151076 $2.50)
120	A Review of Certain Ferrous Castings Applications in Aircraft and Missiles, December 18, 1959 (PB 151077 $1.50)
121	Methods for Conducting Short-Time Tensile, Creep, and Creep-Rupture Tests Under Conditions of Rapid Heating, December 20, 1959 (PB 151078 $1.25)
122	The Welding of Titanium and Titanium Alloys, December 31, 1959 (PB 151079 $1.75)
123	Oxidation Behavior and Protective Coatings for Columbium and Columbium-Base Alloys, January 15, 1960 (PB 151080 $2.25)
124	Current Tests for Evaluating Fracture Toughness of Sheet Metals at High Strength Levels, January 28, 1960 (PB 151081 $2.00)
125	Physical and Mechanical Properties of Columbium and Columbium-Base Alloys, February 22, 1960 (PB 151082 $1.75)
126	Structural Damage in Thermally Cycled René 41 and Astroloy Sheet Materials, February 29, 1960 (PB 151083 $0.75)
127	Physical and Mechanical Properties of Tungsten and Tungsten-Base Alloys, March 15, 1960 (PB 151084 $1.75)
128	A Summary of Comparative Properties of Air-Melted and Vacuum-Melted Steels and Superalloys, March 28, 1960 (PB 151085 $2.75)
129	Physical Properties of Some Nickel-Base Alloys, May 20, 1960 (PB 151086 $2.75)
130	Selected Short-Time Tensile and Creep Data Obtained Under Conditions of Rapid Heating, June 17, 1960 (PB 151088 $2.25)
131	New Developments of the Welding of Metals, June 24, 1960 (PB 151089 $1.25)
132	Design Information on Nickel-Base Alloys for Aircraft and Missiles, July 20, 1960 (PB 151090 $3.00)
133	Tantalum and Tantalum Alloys, July 25, 1960 (PB 151091 $3.00)
134	Strain Aging of Refractory Metals, August 12, 1960 (PB 151092 $1.75)
135	Design Information on 321 [illegible] Stainless Steel for Aircraft and Missiles, August 22, 1960 (PB 151093 $1.25)

DMIC Report Number	Title
136A	The Effects of Alloying Elements in Titanium, Volume A. Constitution, September 15, 1960 (PB 151094 $3.50)
136B	The Effects of Alloying Elements in Titanium, Volume B. Physical and Chemical Properties, Deformation and Transformation Characteristics, May 29, 1961 (AD 260228 $3.00)
137	Design Information on 17-7 PH Stainless Steels for Aircraft and Missiles, September 23, 1960 (PB 151095 $1.00)
138	Availability and Mechanical Properties of High-Strength Steel Extrusions, October 26, 1960 (PB 151097 $1.75)
139	Melting and Casting of the Refractory Metals Molybdenum, Columbium, Tantalum, and Tungsten, November 18, 1960 (PB 151098 $1.00)
140	Physical and Mechanical Properties of Commercial Molybdenum-Base Alloys, November 30, 1960 (PB 151099 $3.00)
141	Titanium-Alloy Forgings, December 19, 1960 (PB 151100 $2.25)
142	Environmental Factors Influencing Metals Applications in Space Vehicles, December 27, 1960 (PB 151101 $1.25)
143	High-Strength-Steel Forgings, January 5, 1961 (PB 151102 $1.75)
144	Stress-Corrosion Cracking – A Nontechnical Introduction to the Problem, January 6, 1961 (PB 151103 $0.75)
145	Design Information on Titanium Alloys for Aircraft and Missiles, January 13, 1961 (PB 151104 $2.25)
146	Manual for Beryllium Prospectors, January 18, 1961 (PB 151105 $1.00)
147	The Factors Influencing the Fracture Characteristics of High-Strength Steel, February 6, 1961 (PB 151106 $1.25)
148	Review of Current Data on the Tensile Properties of Metals at Very Low Temperatures, February 14, 1961 (PB 151107 $2.00)
149	Brazing for High Temperature Service, February 21, 1961 (PB 151108 $1.00)
150	A Review of Bending Methods for Stainless Steel Tubing, March 2, 1961 (PB 151109 $1.50)
151	Environmental and Metallurgical Factors of Stress-Corrosion Cracking in High-Strength Steels, April 14, 1961 (PB 151110 $0.75)
152	Binary and Ternary Phase Diagrams of Columbium, Molybdenum, Tantalum, and Tungsten, April 28, 1961 (AD 257739 $3.50)
153	Physical Metallurgy of Nickel-Base Superalloys, May 5, 1961 (AD 258041 $1.25)
154	Evolution of Ultrahigh-Strength, Hardenable Steels for Solid-Propellant Rocket-Motor Cases, May 25, 1961 (AD 257976 $1.25)
155	Oxidation of Tungsten, July 17, 1961 (AD 263596 $3.00)
156	Design Information on AM-350 Stainless Steel for Aircraft and Missiles, July 28, 1961 (AD 262407 $1.50)
157	A Summary of the Theory of Fracture in Metals, August 7, 1961 (PB 181081 $1.75)
158	Stress-Corrosion Cracking of High-Strength Stainless Steels in Atmospheric Environments, September 15, 1961 (AD 266005 $1.25)
159	Gas-Pressure Bonding, September 25, 1961 (AD 265133 $1.25)
160	Introduction to Metals for Elevated-Temperature Use, October 27, 1961 (AD 268647 $2.50)
161	Status Report No. 1 on Department of Defense Refractory Metals Sheet-Rolling Program, November 2, 1961 (AD 267077 $1.00)
162	Coatings for the Protection of Refractory Metals from Oxidation, November 24, 1961 (AD 271384 $3.50)
163	Control of Dimensions in High-Strength Heat-Treated Steel Parts, November 29, 1961 (AD 270045 $1.00)
164	Semiaustenitic Precipitation-Hardenable Stainless Steels, December 6, 1961 (AD 274803 $2.75)
165	Methods of Evaluating Welded Joints, December [illegible], 1961 (AD 272088 $2.25)
166	The Effect of Nuclear Radiation on Structural Metals, September 15, 1961 (AD 265839 $2.50)
167	Summary of the Fifth Meeting of the Refractory Composite Working Group, March 12, 1962 (AD 274804 $2.00)
168	Beryllium for Structural Applications, 1958-1960, May 18, 1962 (AD 278723 $3.50)
169	The Effect of Molten Alkali Metals on Containment Metals and Alloys at High Temperatures, May 18, 1962 (AD 282932 $1.50)
170	Chemical Vapor Deposition, June 4, 1962 (AD 281[illegible] $[illegible].25)
171	The Physical Metallurgy of Cobalt-Base Superalloys, July 6, 1962 (AD 283450 $2.25)
172	Background for the Development of Materials To Be Used in High-Strength-Steel Structural Weldments, July 31, 1962 (AD 284265 $3.50)
173	New Developments in Welded Fabrication of Large Solid Fuel Rocket-Motor Cases, August 6, 1962 (AD 284829 $1.00)
174	Electron-Beam Processes, September 15, 1962 (AD [illegible] $[illegible])
175	Summary of the Sixth Meeting of the Refractory Composites Working Group, September 24, 1962 (AD 287029 $1.75)
176	Status Report No. 2 on Department of Defense Refractory Metals Sheet-Rolling Program, October 15, 1962 (AD [illegible] $1.25)
177	Thermal Radiative Properties of Selected Materials, November 15, 1962, Vol. I (AD 294345 $3.50)
177	Thermal Radiative Properties of Selected Materials, November 15, 1962, Vol. II (AD 294346 $4.00)
178	Steels for Large Solid-Propellant Rocket-Motor Cases, November 26, 1962
179	A Guide to the Literature on High-Velocity Metalworking, December 3, 1962
180	Design Considerations in Selecting Materials for Large Solid-Propellant Rocket-Motor Cases, December 10, 1962
181	Joining of Nickel-Base Alloys, December [illegible], 1962
182	Structural Considerations in Developing Refractory Metal Alloys, January 31, 1963
183	Binary and Ternary Phase Diagrams of Columbium, Molybdenum, Tantalum, and Tungsten (Supplement to DMIC Report 152), February 7, 1963
184	Summary of the Seventh Meeting of the Refractory Composites Working Group, May 30, 1963
185	The Status and Properties of Titanium Alloys for Structures, June 11, 1963
186	The Effect of Fabrication History and Microstructure on the Mechanical Properties of Refractory Metals and Alloys, July 19, 1963
187	The Application of Ultrasonic Energy in the [illegible] of Metals, August 16, 1963

Battelle Memorial Institute, Defense Metals Information Center, Columbus, Ohio. THE ENGINEERING PROPERTIES OF COLUMBIUM AND COLUMBIUM ALLOYS, by F. F. Schmidt and H. R. Ogden. September 6, 1963. [237] pp incl. illus., tables, refs. DMIC Report 188. [AF 33(616)-7747]

Unclassified report

This report presents the results of a state-of-the-art survey covering columbium and 18 of its most promising alloys. All data are given in tabular and graphical form covering some of the more important physical, mechanical, and metallurgical properties for each material. References are given at the conclusion of each material section.

UNCLASSIFIED

1. Columbium
2. Physical Properties
3. Mechanical Properties
4. Metallurgical Properties

I. Battelle Memorial Institute
II. Defense Metals Information Center
III. Contract AF 33(616)-7747

UNCLASSIFIED

Battelle Memorial Institute, Defense Metals Information Center, Columbus, Ohio. THE ENGINEERING PROPERTIES OF COLUMBIUM AND COLUMBIUM ALLOYS, by F. F. Schmidt and H. R. Ogden. September 6, 1963. [237] pp incl. illus., tables, refs. DMIC Report 188. [AF 33(616)-7747]

Unclassified report

This report presents the results of a state-of-the-art survey covering columbium and 18 of its most promising alloys. All data are given in tabular and graphical form covering some of the more important physical, mechanical, and metallurgical properties for each material. References are given at the conclusion of each material section.

UNCLASSIFIED

1. Columbium
2. Physical Properties
3. Mechanical Properties
4. Metallurgical Properties

I. Battelle Memorial Institute
II. Defense Metals Information Center
III. Contract AF 33(616)-7747

UNCLASSIFIED

Battelle Memorial Institute, Defense Metals Information Center, Columbus, Ohio. THE ENGINEERING PROPERTIES OF COLUMBIUM AND COLUMBIUM ALLOYS, by F. F. Schmidt and H. R. Ogden. September 6, 1963. [237] pp incl. illus., tables, refs. DMIC Report 188. [AF 33(616)-7747]

Unclassified report

This report presents the results of a state-of-the-art survey covering columbium and 18 of its most promising alloys. All data are given in tabular and graphical form covering some of the more important physical, mechanical, and metallurgical properties for each material. References are given at the conclusion of each material section.

UNCLASSIFIED

1. Columbium
2. Physical Properties
3. Mechanical Properties
4. Metallurgical Properties

I. Battelle Memorial Institute
II. Defense Metals Information Center
III. Contract AF 33(616)-7747

UNCLASSIFIED

Battelle Memorial Institute, Defense Metals Information Center, Columbus, Ohio. THE ENGINEERING PROPERTIES OF COLUMBIUM AND COLUMBIUM ALLOYS, by F. F. Schmidt and H. R. Ogden. September 6, 1963. [237] pp incl. illus., tables, refs. DMIC Report 188. [AF 33(616)-7747]

Unclassified report

This report presents the results of a state-of-the-art survey covering columbium and 18 of its most promising alloys. All data are given in tabular and graphical form covering some of the more important physical, mechanical, and metallurgical properties for each material. References are given at the conclusion of each material section.

UNCLASSIFIED

1. Columbium
2. Physical Properties
3. Mechanical Properties
4. Metallurgical Properties

I. Battelle Memorial Institute
II. Defense Metals Information Center
III. Contract AF 33(616)-7747

UNCLASSIFIED

UNCLASSIFIED

UNCLASSIFIED