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BMI-X-10264

LITERATURE SURVEY

on

DILUTE URANIUM ALLOYS

for

SANDIA BOOSTER CONCEPT

to

SANDIA CORPORATION

by

J. M. Fackelmann, A. A. Bauer, and D. P. Moak

July, 1969

BATTELLE MEMORIAL INSTITUTE
Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201

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cc: S. J. Paprocki

A. A. Bauer

W. H. Pfeifer

D. P. Moak

D. L. Keller

J. E. Davis/AEC Files

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J. M. Fackellmann (5)

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August 25, 1969

BMI-X-10264

Mr. A. Hasenkamp
Organization 5223
Reactor Development Division
Sandia Corporation
Sandia Base
Albuquerque, New Mexico 87115

Dear Mr. Hasenkamp:

One portion of the program which Battelle is conducting under Sandia Purchase Order ASB 50-0051 concerns a literature survey on potential fuels for the Sandia Booster Concept. The enclosed report provides a summary of the data that were found on uranium alloys with alloy additions limited to 10 w/o or less.

As you will recall, the raw data from which this summary has been prepared were given to you in rough form several months ago. The purpose of the enclosed report is to make some attempt to interpret and evaluate those data and to present what we believe are the most accurate of the property information available.

A review of the classified literature revealed a rather small amount of additional data. A separate letter has been prepared covering this information and is being forwarded to you concurrent with this report.

Your questions or comments concerning this report will be welcomed.

Very truly yours,

D. L. Keller
Associate Manager
Materials Engineering Department

DLK/scr
Enc. (9)

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LITERATURE SURVEY ON DILUTE URANIUM ALLOYS

J. M. Fackelmann, A. A. Bauer, and D. P. Moak

SUMMARY

Although data on the uranium-molybdenum system are fairly complete, many of the mechanical properties reported may have been affected by uncontrolled stress-corrosion effects which are still not fully understood. The elevated-temperature data on the uranium-niobium alloy are rather incomplete. Detailed studies on the effect of aging and strain rate on mechanical properties are lacking for the uranium-zirconium system. Although limited information suggests some potential for uranium-chromium alloys as a booster fuel, the available property data are extremely limited. A good deal of pertinent research has been performed on Mulberry alloy (U-7.5 w/o Nb-2.5 w/o Zr) but this ternary alloy is complex and there are still a lot of gaps in the available data.

A problem common to all of the metastable gamma alloys is that sufficient attention has not been given to transformations that may be occurring during testing at elevated temperature. Hence, many of the reported data on gamma-phase alloys become suspect.

INTRODUCTION

The literature has been reviewed for the purpose of compiling property data on uranium-base alloys. The properties of interest were: elastic modulus, specific heat, thermal-expansion coefficient, density, yield strength, tensile strength, Poisson's ratio, tensile ductility, thermal conductivity, effect of strain rate on strength, effect of thermal cycling on dimensional stability, stress-corrosion susceptibility, and time temperature-transformation behavior. In addition to data on the effects of alloying on these properties, information on the effects of temperature and heat treatment was obtained. The most reliable data are presented wherever it was possible to determine reliability.

The purpose of this study was to evaluate uranium-alloy fuels for the booster concept, in which the alloying addition is limited to 10 w/o or less.

The systems considered were uranium-molybdenum, uranium-niobium, uranium-zirconium, uranium-chromium, and uranium-7.5 w/o niobium-2.5 w/o zirconium (Mulberry alloy).

The unclassified literature from 1947 to the present was surveyed. In addition, a classified supplement has been prepared. The unclassified portion of the study follows. Some areas recommended for research where literature data are inadequate or conflicting are discussed following the survey section.

DATA COMPILED ON PROGRAM

This report is divided into sections according to alloying addition: Section A contains uranium-molybdenum data, Section B contains uranium-niobium data, Section C contains uranium-zirconium data, Section D contains uranium-chromium data, and Section E contains data for uranium-7.5 w/o niobium-2.5 w/o zirconium (Mulberry alloy).

The setup of the five sections is identical. An overview calling out the high points of the data found in the survey for that alloy is followed by a discussion where an attempt is made to interpret and evaluate the data. Then a set of figures containing the specific data is presented. More details are found in the set of tables that is introduced after the set of figures. A list of references concludes the section.

SECTION A. URANIUM-MOLYBDENUM ALLOYS

The anisotropic properties of uranium are largely eliminated by alloying with certain elements. Molybdenum is a favored alloying element, serving to stabilize the cubic γ phase. The principal advantages of uranium-molybdenum fuels are dimensional stability, corrosion resistance, and high-temperature strength. Unfortunately, these alloys are susceptible to stress-corrosion effects, an important limitation.

Phase Relationships

Phase relationships in the uranium-molybdenum system were summarized by Rough and Bauer(A-1), and refined by Dwight later(A-2). Dwight's phase diagram is shown in Figure A-1. The γ' phase is tetragonal and may be considered an ordered form of the cubic γ . Isothermal transformation curves that show the start of transformation for various uranium-molybdenum alloys are given in Figure A-2. The γ formed initially with α differs in composition from the original γ and is metastable. A transformation diagram for uranium-10 w/o molybdenum that describes these changes more fully is shown in Figure A-3.

Corrosion

Molybdenum additions to uranium greatly improve its resistance to general corrosion, but can make the alloys formed susceptible to serious stress-corrosion attack. The corrosion rates of several uranium-molybdenum alloys in water are plotted in Figure A-4.

By way of comparison, unalloyed uranium corrodes at a rate of 1 mg/(cm²)(hr) in 90 C water, a much greater rate than that of the alloys. Similar relationships are also evident in an air environment at 500 C. Here, uranium-10 w/o molybdenum corrodes at a rate of 0.48 mg/(cm²)(hr), as compared to 90 mg/(cm²)(hr) for unalloyed uranium(A-3). The stress-corrosion effects on uranium-molybdenum alloys are manifested in room-temperature air with stresses as low as 30 percent of the yield strength. The relationship of stress level to failure time in room-temperature air for uranium-10 w/o molybdenum is plotted in Figure A-5. As may be seen, time for failure is inversely proportional to stress. At temperatures above ambient (to 100 C) the cracking rate was found to increase, and at lower temperatures (to 10 C) a decrease was noted. (A-4) According to Pridgeon(A-4), the presence of oxygen is necessary for stress-corrosion effects to occur.

Dimensional Stability

Anisotropic properties and preferred orientation effects associated with the alpha phase of unalloyed uranium lead to growth and distortion during thermal cycling. These effects are greatly reduced by alloying the uranium with molybdenum. The molybdenum produces this improvement by stabilizing the gamma phase. The effect of thermal

cycling on the dimensional changes of a series of uranium-molybdenum alloys is shown in Table A-1.

Physical Properties

Thermal Expansion

Thermal expansion coefficients of uranium-molybdenum alloys are listed in Tables A-2 and A-3, and plotted in Figures A-6 and A-7.

Specific Heat

Specific heat values for uranium-10 w/o molybdenum are given in Table A-4. The effect of varying molybdenum content on specific heat is plotted in Figure A-8.

Thermal Conductivity

Thermal conductivity values for various uranium-molybdenum alloys are listed in Table A-5, and plotted in Figure A-9. The effect of irradiation is shown in Table A-6.

Density

Densities of uranium-molybdenum alloys as a function of temperature are listed in Table A-7.

Mechanical Properties

A great deal of tensile property data have been generated for uranium-molybdenum alloys. Some of the variables studied have been molybdenum content, fabrication history, temperature, etc. A serious problem in interpreting these data involves the great spread in results. For example, room-temperature ductility (percentage elongation) values reported for gamma-annealed uranium-10 w/o molybdenum varied from <1 percent (A-5) to about 20 percent (A-6). The former test had been conducted in air, while the latter was conducted in vacuum. Alloy purity and stress-corrosion effects from air that depend on the particular environment can affect the results as discussed earlier. The importance of stress-corrosion effects has been appreciated only relatively recently (A-4, A-6, A-7, A-8), and data obtained under conditions where the test environment is controlled to control these effects are limited.

Tensile Strength

Hoge (A-7) conducted dynamic and static tensile tests on uranium-10 w/o molybdenum of controlled purity and fabrication history. Materials were fabricated at γ temperatures. At high strain rates stress-corrosion effects were unimportant, while they were manifested at lower strain rates. His results are shown in Tables A-8 through

A-11 and Figures A-10 through A-14. The "peak stress" values reported are actually ultimate tensile strengths for this alloy. (This term is used to describe the dynamic yield phenomenon.) It is defined as the first stress level where sufficient plastic strain has occurred so that the tangent to the stress-strain curve is parallel to the strain axis.

Reliable tensile-strength values of uranium-10 w/o molybdenum as a function of fabrication history and carbon content are given in Table A-12 and Figure A-15.

Additional tensile strength data are given in Tables A-13 and A-14.

Yield Strength

Owing to the shape of the stress-strain curve, the peak stress is also the approximate 0.2 percent yield strength of the material, never exceeding this property by more than 4 percent. Peak stress values are shown in Tables A-8 through A-11 and Figures A-10 through A-14.

Additional yield-strength data are given in Tables A-13 and A-14.

Ductility

The effect of strain rate and test environment on ductility is plotted in Figure A-16. This plot shows a ductility minimum at low strain rates in air which may be caused by stress-corrosion effects, which are eliminated by testing in vacuum. At much higher strain rates, ductility becomes inversely proportional to strain rate as a result of dynamic yielding effects. The effect of molybdenum content on the tensile properties is given in Table A-15. The great variance results from uncontrolled effects, as discussed above, and these results should be used with great discretion.

Reliable ductility values of uranium-10 w/o molybdenum as a function of fabrication history and carbon content are given in Table A-12 and Figure A-15.

Additional ductility data are given in Tables A-13 and A-14.

Young's Modulus

Young's modulus is plotted as a function of heat treatment and molybdenum content in Figure 17. Additional Young's modulus measurements are given in Tables A-13 and A-14.

Poisson's Ratio

Poisson's ratio data are given in Tables A-13 and A-14.

Discussion

Many of the mechanical properties of uranium-molybdenum alloys might have been affected by uncontrolled stress-corrosion effects and impurity levels. These properties need to be redetermined where this has not already been done in the classified literature. More study of the stress-corrosion mechanism is also needed in order to obtain a precise understanding of the exact mechanism involved.

FIGURE A-1. PHASE DIAGRAM OF THE URANIUM-MOLYBDENUM SYSTEM^(A-2)

FIGURE A-2. ISOTHERMAL TRANSFORMATIONS OF URANIUM-MOLYBDENUM ALLOYS^(A-9)

FIGURE A-3. ISOTHERMAL TRANSFORMATION DIAGRAM FOR THE URANIUM-10 w/o MOLYBDENUM ALLOY QUENCHED TO TEMPERATURE FROM 900 C(A-10)

FIGURE A-4. RATE OF CORROSION IN WATER OR STEAM AS A FUNCTION OF TEST TEMPERATURE FOR SPECIMENS OF URANIUM-MOLYBDENUM ALLOYS QUENCHED FROM THE γ REGION(A-11)

FIGURE A-5. DELAYED FAILURE CHARACTERISTICS OF URANIUM-10 w/o MOLYBDENUM IN THE GAMMA CONDITION(A-6, A-8)

FIGURE A-6. EFFECT OF MOLYBDENUM ADDITION TO URANIUM ON THERMAL EXPANSION COEFFICIENT BETWEEN 100 AND 400 C(A-6)

FIGURE A-7. EFFECT OF IRRADIATION ON LINEAR THERMAL EXPANSION OF URANIUM-10 w/o MOLYBDENUM(A-12)

FIGURE A-8. EFFECT OF MOLYBDENUM ADDITION TO URANIUM ON SPECIFIC HEAT AT VARIOUS TEMPERATURES(A-13, A-14)

FIGURE A-9. EFFECT OF TEMPERATURE ON THERMAL CONDUCTIVITY OF UNALLOYED URANIUM^(A-15) AND URANIUM-10 w/o MOLYBDENUM^(A-16)

FIGURE A-10. PEAK STRESS VERSUS STRAIN RATE FOR URANIUM-10 w/o MOLYBDENUM IN EXTRUDED CONDITION(A-7)

FIGURE A-11. PEAK STRESS VERSUS STRAIN RATE FOR URANIUM-10 w/o MOLYBDENUM IN AS-CAST CONDITION WITH HIGH CARBON CONTENT(A-7)

FIGURE A-12. PEAK STRESS VERSUS STRAIN RATE FOR URANIUM-10 w/o MOLYBDENUM IN HOT-ROLLED CONDITION(A-7)

FIGURE A-13. PEAK STRESS VERSUS STRAIN RATE FOR URANIUM-10 w/o MOLYBDENUM IN AS-CAST CONDITION WITH LOW CARBON CONTENT(A-7)

FIGURE A-14. PEAK STRESS VERSUS TEST TEMPERATURE FOR A CONSTANT STRAIN RATE OF 20 IN./IN./SEC FOR URANIUM-10 w/o MOLYBDENUM (A-7)

FIGURE A-15. EFFECT OF TEMPERATURE ON TENSILE PROPERTIES OF AS-CAST URANIUM-10 w/o MOLYBDENUM WITH A CARBON CONTENT OF 880 PPM (A-7)

FIGURE A-16. THE EFFECT OF STRAIN RATE ON DUCTILITY OF URANIUM-10 w/o MOLYBDENUM^(A-6)

FIGURE A-17. EFFECT OF MOLYBDENUM ADDITION ON YOUNG'S MODULUS AT ROOM TEMPERATURE(A-17)

TABLE A-1. RESULTS OF CYCLIC HEAT TREATMENT OF URANIUM-MOLYBDENUM ALLOYS PREPARED BY DIFFERENT METHODS(A-18)

Molybdenum, w/o	Technology of Preparation	Diameter of Specimens, mm	Change in Length, percent	Change in Diameter, percent	Density, g per cm ³		Condition of Specimens After 500 Cycles Between 200 and 720 C
					Initial	Final	
Nil	Subjected to β -treatment	9.5	9.09 to 56.7	13.2 to 18.4	18.82 to 18.85	17.95 to 18.70	Increasing in all directions, formation of projections, bending
11.4	Hot rolled	9.5	-3.67	+8.48	18.45	--	Specimen is bent, warped, has an oval shape and rough surface
Nil	Cold pressed and sintered	9.5	+12.98	+16.76	18.49	13.34	Mushroom-shaped specimen
0.5	Ditto	5.1	+11.3	+1.04	17.57	17.12	Slightly roughened surface
1.0	"	5.1	+0.97	+1.60	17.88	17.42	Ditto
1.2	"	9.5	-1.33	+1.72	18.56	18.49	"
1.4	"	9.5	+0.8	+1.07	18.52	18.43	Smooth surface
1.75	"	9.5	+0.66	+0.87	17.97	17.73	Ditto
2.0	"	9.5	-0.93	-1.33	18.57	18.36	"
2.5	"	9.5	-0.13	+0.88	18.30	18.13	Slightly crumpled surface
3.0	"	9.5	+2.66	+0.96	18.09	18.03	Ditto
3.5	"	9.5	-0.26	-0.54	18.12	17.98	Smooth surface
3.75	"	9.5	-1.07	+0.35	17.62	17.73	Ditto
4.0	"	9.5	+0.67	+0.61	16.78	16.77	Slightly crumpled surface
4.5	"	9.5	+0.60	0	17.57	17.48	Smooth surface
6.0	"	5.1	+0.10	0	16.75	16.71	Unchanged
11.0	"	5.1	-0.03	0	16.91	16.94	Unchanged

TABLE A-2. INSTANTANEOUS COEFFICIENT OF LINEAR THERMAL EXPANSION FOR A WROUGHT URANIUM-10 w/o MOLYBDENUM ALLOY(A-19)

Temperature, C	Linear Thermal Expansion Coefficient, $10^{-6}/C$	
	Longitudinal Direction	Transverse Direction
25	11.5	11.9
100	12.2	13.0
200	13.2	14.6
300	14.2	16.0
400	15.2	17.6
500	16.2	19.0
550	16.6	19.8

TABLE A-3. LINEAR THERMAL EXPANSION COEFFICIENT FOR CAST URANIUM-10 w/o AND 12 w/o MOLYBDENUM ALLOYS(A-20, 21)

Nominal Composition, w/o molybdenum	Temperature Range, C	Average Linear Thermal Expansion Coefficient, $10^{-6}/C$
10	25-100	11.5
	25-200	11.75
	25-300	12.4
	25-400	12.7
	25-500	13.0
	25-600	13.5
12(a)	20-100	8.95
	20-200	10.45
	20-300	11.59
	20-400	12.11
	20-500	12.56
	20-600	13.08

(a) Heated 1 hr at 800 C and water quenched.

TABLE A-4. SPECIFIC HEAT OF GAMMA-PHASE URANIUM-10 w/o MOLYBDENUM(A-13)

Temperature, C	Specific Heat, cal/(g)(C)
0	0.0322
100	0.0339
200	0.0357
300	0.0375
400	0.0393
500	0.0410
600	0.0428
700	0.0446
800	0.0463
900	0.0481
1000	0.0499

TABLE A-5. THERMAL CONDUCTIVITY OF URANIUM-MOLYBDENUM ALLOYS

Nominal Composition, w/o molybdenum	Temperature, C	Thermal Conductivity, cal/(sec)(cm)(C)	Reference
0	20	0.066	A-15
0	100	0.068	A-15
0	200	0.070	A-15
0	300	0.075	A-15
0	400	0.084	A-15
0	500	0.090	A-15
0	600	0.098	A-15
0	700	0.107	A-15
0	800	0.115	A-15
0.2	200	0.064	A-22
0.2	300	0.071	A-22
0.2	400	0.078	A-22
0.2	500	0.085	A-22
0.2	550	0.089	A-22
1.7	200	0.055	A-22
1.7	300	0.065	A-22
1.7	400	0.074	A-22
1.7	500	0.084	A-22
8	50	0.034	A-23
10	20	0.029	A-16
10	100	0.034	A-16
10	200	0.041	A-16
10	400	0.055	A-16
10	600	0.073	A-16
10	800	0.090	A-16

TABLE A-6. EFFECT OF IRRADIATION ON THE THERMAL CONDUCTIVITY OF URANIUM-10 w/o MOLYBDENUM(A-16)

Burnup, a/o	Thermal Conductivity(a)	
	W/(Cm)(C)	Cal/(Sec)(Cm)(C)
0	0.17	0.041
0.36	0.17	0.041
0.50	0.15	0.036
0.97	0.15	0.036
1.2	0.15	0.036

(a) Presumably at room temperature. Value for 0 a/o burnup does not agree well with other room-temperature values for unirradiated gamma-phase uranium-10 w/o molybdenum.

TABLE A-7. DENSITIES OF GAMMA-PHASE URANIUM-10 w/o MOLYBDENUM AND UNALLOYED URANIUM

Composition	Temperature, C	Density(a), g per cm ³	Reference
Unalloyed uranium	20	19.07	A-19
	100	19.0	A-19
	200	18.9	A-19
	300	18.82	A-19
	400	18.7	A-19
	500	18.55	A-19
	600	18.42	A-19
	700	18.15	A-19
Uranium-10 w/o molybdenum	20	17.12	A-24
	100	17.06	A-24
	200	16.97	A-24
	300	16.88	A-24
	400	16.79	A-24
	500	16.71	A-24
	600	16.62	A-24
	700	16.53	A-24
Unalloyed uranium	20	18.8(b)	A-25
Uranium-2.5 w/o molybdenum	20	18.1(b)	A-25
Uranium-5.0 w/o molybdenum	20	17.7(b)	A-25
Uranium-7.5 w/o molybdenum	20	17.4(b)	A-25
Uranium-10 w/o molybdenum	20	17.2(b)	A-25

(a) X-ray densities unless specified otherwise.

(b) Density measured directly.

TABLE A-8. HIGH-STRAIN-RATE TENSILE TEST RESULTS ON URANIUM-10 w/o MOLYBDENUM
IN THE γ -EXTRUDED CONDITION(A-7)

Temperature, F	$\dot{\epsilon}(a)$, in./in./sec	σ_{peak} , ksi	$\dot{\epsilon}(b)$, in./in./sec	$\epsilon_{\text{rupture}}$, percent	σ_{rupture} , ksi	Failure Mode
75	34	200(c)	33	6.0	--	Ductile
75	--	215	--	--	135	Ductile
75	39(c)	206	35	7.5	139	Ductile
75	35	201	34	6.0	135	Ductile
75	19	190	22	6.0	143	Ductile
75	11	190	10	5.8	140	Ductile, rough fracture
75	16	191	16	6.2	130	Ductile
75	37	201	37	6.2	138.5	Ductile
75	65(c)	221	--	--	129	Ductile
75	95	230	280	6.3	125	Ductile
600	40	127	36	8.0	61.5	Ductile
600	22(c)	121	20	--	69	Ductile
600	17	114	22	9.0	68	Ductile
75	4.8×10^{-5}	129	4.8×10^{-4}	14.0	101	Ductile
75	0.057	168	0.057	--	108	Ductile
75	4.8×10^{-5}	136	4.8×10^{-4}	18.0	107	Very ductile
600	0.057	80.5	0.057	23.0	65	Very ductile
300	0.057	106	0.057	16.0	81	Ductile
300	42	156	60	6.3	90	Ductile
600	89	164	120	9.3	79	Ductile
75	50	209	48	4.5	150	Rough fracture

(a) Average value to peak stress.

(b) Average value from peak to rupture stress.

(c) Approximate value.

TABLE A-9. HIGH-STRAIN-RATE TENSILE TEST RESULTS ON AS-CAST URANIUM-10
w/o MOLYBDENUM CONTAINING 880 PPM CARBON(A-7)

Temperature, F	$\dot{\epsilon}$ (a), in./in./sec	σ_{peak} , ksi	$\dot{\epsilon}$ (b), in./in./sec	$\epsilon_{\text{rupture}}$, percent	σ_{rupture} , ksi	Failure Mode
75	34	192	34	2.8	192	Brittle, fine fracture
75	20	145	20	1.8	145	Brittle, fine fracture
75	4.8×10^{-5}	120.4	4.8×10^{-4}	12.5	107	Ductile
75	4.8×10^{-5}	118.9	4.8×10^{-4}	5	111	Ductile
75	4.8×10^{-5}	116.8	4.8×10^{-4}	5	106	Ductile
200	30	127.3	30	1.0	127.3	Brittle, coarse fracture
200	36	178.8	42	7.5	102	Ductile, fine fracture
75	30	174.2	30	1.5	174.2	Brittle, coarse fracture
200	42	152	59	2.0	131.2	Brittle - ductile, fine fracture
200	49	179.2	49	2.5	163	Brittle - ductile, fine fracture
200	60	145.3	117	2.5	136.3	Brittle - ductile, fine fracture
300	46	160	81	2.0	135.3	Brittle - ductile, fine fracture
300	40	146.5	117	2.5	137.8	Brittle, coarse fracture near threads
75	22	142.3	22	1.0	142.3	Brittle
75	28	163	28	1.0	163	Brittle, coarse fracture near threads
600	9	91	21	--	75	Ductile, fine fracture
600	4	84	18	--	60	Ductile, fine fracture
600	6.5	90.2	16	11.5	72	Ductile, fine fracture
600	7	96	14	11.7	64	Ductile, fine fracture
200	4.8×10^{-5}	96.2	4.8×10^{-4}	12.0	94	Ductile
300	4.8×10^{-5}	90.4	4.8×10^{-4}	12.0	90.2	Ductile
600	4.8×10^{-5}	62.7	4.8×10^{-4}	14.0	62.7	Ductile
600	4.8×10^{-5}	62.8	4.8×10^{-4}	16.0	62.7	Ductile
600	5.7×10^{-2}	74	5.7×10^{-2}	17.0	61	Ductile
75	36	103	37	14.0	67	Ductile

(a) Average strain rate to peak stress.

(b) Average strain rate from peak to rupture.

TABLE A-10. HIGH-STRAIN-RATE TENSILE TEST RESULTS ON URANIUM-10 w/o
MOLYBDENUM IN THE γ -ROLLED CONDITION(A-7)

Temperature, F	$\dot{\epsilon}(a)$, in. / in. / sec	σ_{peak} , ksi	$\dot{\epsilon}(b)$, in. / in. / sec	$\epsilon_{\text{rupture}}$, percent	σ_{rupture} , ksi	Failure Mode
75	4.8×10^{-5}	141.8	4.8×10^{-4}	23	96	Ductile
75	0.057	165(c)	0.057	--	165	Brittle, fracture in threads
300	0.057	129	0.057	22.5	81	Ductile
600	4.8×10^{-5}	88	4.8×10^{-4}	--	88	Fracture in fillet radius
600	0.057	91	0.057	23	76	Ductile
300	0.057	98(c)	0.057	--	98	Brittle, fracture in threads
75	33	171(c)	33	0.4	171	Brittle, failed in threads
75	19	179(c)	19	0.5	179	Brittle, failed in threads
600	99	171	98	9.0	73	Ductile
600	73	157	70	11.0	70	Ductile
600	45	137	45	11.8	71	Ductile
600	27	125	29	12.6	72	Ductile
300	23	162	24	9.6	91	Ductile
300	31	166	31	7.5	93	Rough but ductile
300	75	189	75	6.8	115	Slightly rough
300	--	164(c)	--	0.5	164	Fracture in threads
300	65	170(c)	65	0.4	170	Fracture in threads
75(d)	45	190(c)	45	0.3	190	Fracture in threads
75(d)	23	185(c)	23	0.3	185	Fracture in threads
75(d)	0.057	162	0.057	17	90.5	Ductile
75(e)	11	196	14	6.2	105	Ductile
75(e)	4.8×10^{-4}	145	4.8×10^{-4}	23.0	140	Ductile
75(e)	25	141(c)	25	0.5	141	Fracture in threads
75(e)	19	186(c)	19	0.5	186	Fracture in threads
75(e)	15	189(c)	15	0.3	189	Fracture in threads

(a) Average value to peak stress.

(b) Average value from peak to rupture stress.

(c) Fractured in threads.

(d) Given special high-vacuum heat treatment.

(e) Given special short-time heat treatment.

TABLE A-11. HIGH-STRAIN-RATE TENSILE TEST RESULTS ON AS-CAST URANIUM-10 w/o MOLYBDENUM CONTAINING 71 PPM CARBON(A-7)

Temperature, F	$\dot{\epsilon}(a)$, in./in./sec	σ_{peak} , ksi	$\dot{\epsilon}(b)$, in./in./sec	$\epsilon_{\text{rupture}}$, percent	σ_{rupture} , ksi	Failure Mode
75	21	194	22	2.5	179	Brittle
75	27	201	28	2.5	174	Brittle
75	39	207	32	2.5	192	Brittle
75	70	185	70(c)	2.0	170	Brittle
75	65	205(c)	65	0.4(c)	205	Brittle, fracture in threads
600	12	118	11	8.5(c)	69	Ductile, rough
600	62	150	50	3.0	72	Slightly ductile
600	37	128	56	10.0	66	Ductile
600	0.057	78	0.057	26	76	Very ductile
600	4.8×10^{-5}	72.5	4.8×10^{-4}	18	71	Ductile

(a) Average value to peak stress.

(b) Average value from peak to rupture stress.

(c) Approximate value.

TABLE A-12. EFFECT OF COMPOSITION, FABRICATION HISTORY,
AND TEMPERATURE ON TENSILE PROPERTIES OF
URANIUM-10 w/o MOLYBDENUM AT A STRAIN
RATE OF 3×10^{-3} IN./IN./MIN(A-7)

Fabrication Condition	Carbon Content, ppm	Test Temperature, C	Tensile Strength, ksi	Elongation, percent
Extruded 930 C, vacuum heat treated 760 C	228	25	129	14
Extruded 930 C, vacuum heat treated 760 C	228	25	136	18
Rolled 980 C, vacuum heat treated 150 C	98	25	142	23
As Cast	880	25	120	13
As Cast	880	25	119	5
As Cast	880	25	117	5
As Cast	880	200	96.2	12
As Cast	880	300	90.4	12
As Cast	880	600	62.7	14
As Cast	880	600	62.8	16
As Cast	71	600	72.5	18

TABLE A-13. ROOM-TEMPERATURE MECHANICAL PROPERTIES OF GAMMA-PHASE URANIUM-MOLYBDENUM ALLOYS

Composition, w/o molybdenum	Heat Treatment(a)	Ultimate Tensile Strength, ksi	Yield Strength, ksi	Elongation, percent	Reduction in Area, percent	Strain Rate	Young's Modulus, 10 ⁶ psi	Poisson's Ratio	Reference
9.18	3 days 950 C, oil quenched	114.4	112 (0.1%)	9.0	31	6%/min	--	--	A-26
9.18	3 days 950 C, oil quenched	143	143 (0.1%)	11.5	29	6%/min	--	--	A-26
10	Presumably γ quenched	141.8	138.6 (0.2%)	1.5 (in 2 in.)	33.8	--	12.8	--	A-27
10	Presumably γ quenched	139.0	136.4 (0.2%)	1.9 (in 2 in.)	36.8	--	12.2	--	A-27
10	Annealed at 900 C for 7 days(b)	99.6	--	0.1 (in 1.2 in.)	--	--	12.6	0.35	A-28
10	Quenched from 800 C 1 hr at 350 C(c)	139.7	--	9.0 (in 1 in.)	--	--	13.2	0.397(d)	A-28
10	1 hr at 800 C, A. C.	139.3	--	8.0 (in 1 in.)	--	--	13.0	0.319(d)	A-28
10	Bend test data	--	--	--	--	--	--	0.324	A-27
10	Bend test data	--	--	--	--	--	--	0.326	A-27
10.25	3 days 950 C, oil quenched	145.6	144.0 (0.1%)	8.0	23.0	--	--	--	A-26
10.25	3 days 950 C, Hg quenched	143.0	142.0 (0.1%)	11.5	29.0	--	--	--	A-26
10.9	Cast and heated 7 days at 900 C(b)	88.2	--	1.4 (1.2 in.)	--	--	13.6	0.35	A-28
10.9	Coextruded(b)	155.4	--	7.5	--	--	--	--	A-28
11.85	900 C, oil quenched	157.2	157.2 (0.1%)	7.0	10	--	--	--	A-26
12	24 hr 900 C, W. Q.	167	167 (0.5%)	9.0	42	0.005 in./min	--	--	A-29

A-23

TABLE A-13. (Continued)

Composition, w/o molybdenum	Heat Treatment	Ultimate Tensile Strength, ksi	Yield Strength, ksi	Elongation, percent	Reduction in Area, percent	Strain Rate	Young's Modulus, 10 ⁶ psi	Poisson's Ratio	Reference
12	24 hr 900 C, W. Q.	159	159 (0.5%)	3.6	21	0.005 in./min	--	--	A-29
12	24 hr 900 C, W. Q.	165	165 (0.5%)	6.0	37	0.005 in./min	--	--	A-29
12	24 hr 900 C, W. Q.	149	149 (0.5%)	5.1 (in 1.5 in.)	30	0.033 in./min	--	--	A-30
13.5	Cast and heated 7 days 900 C ^(b)	47	--	Nil	--	--	13.5	0.35	A-28

(a) W. Q. = water quenched

A. C. = air cooled.

(b) Low-purity starting materials used.

(c) Gamma phase may have partially transformed.

(d) Accuracy of value questionable.

TABLE A-14. ELEVATED-TEMPERATURE MECHANICAL PROPERTIES OF GAMMA-PHASE URANIUM-MOLYBDENUM ALLOYS

Nominal Composition, w/o molybdenum	Heat Treatment and Fabrication History ^(a)	Test Temperature, C	Ultimate Tensile Strength, ksi	Yield Strength, ksi	Elongation, percent	Reduction in Area, percent	Strain Rate, in./min	Young's Modulus, 10 ⁶ psi	Poisson's Ratio	Reference
9	1 hr 800 C, W. Q.	288	71.7	--	13.3	36.4	--	--	--	A-31
9	1 hr 800 C, W. Q.	538	57.1	--	3.4 ^(b)	23.6	--	--	--	A-31
10	1 hr 800 C, W. Q., 1 hr 350 C ^(c)	121	107.	--	11 (in 1 in.)	--	--	12.07	0.234 ^(d)	A-32
10	1 hr 800 C, W. Q., 1 hr 350 C ^(c)	121	101.6	--	12.5 (in 1 in.)	--	--	11.52	0.388 ^(d)	A-32
10	--	250	91.6	86.3	10.5 (in 1 in.)	45.2	0.02	12.3	--	A-27
10	--	250	90.8	85.2	4.5 (in 2 in.)	45.7	0.02	11.8	--	A-27
10	1 hr 800 C, W. Q., 1 hr 350 C ^(c)	260	92.4	--	10.5 (in 1 in.)	--	--	10.96	0.432 ^(d)	A-32
10	1 hr 800 C, W. Q., 1 hr 350 C ^(c)	260	91.6	--	11.0 (in 1 in.)	--	--	10.97	0.583 ^(d)	A-32
10	1 hr 800 C, W. Q., 1 hr 350 C ^(c)	399	84.7	--	5.0 (in 1 in.)	--	--	8.4	1.192 ^(d)	A-32
10	1 hr 800 C, A. C.	399	78.9	--	3.0 (in 1 in.)	--	--	6.84	0.986 ^(d)	A-32
10	--	500	68.5	65.7	1.3	4.7	--	--	--	A-5
10	--	500	66.8	63.9	1.4	6.1	--	--	--	A-5
10	--	500	72.2	72.2	1.2	7.4	--	--	--	A-5
10	--	500	69.4	66.2	1.5 (in 1 in.)	15.1	0.02	9.4	--	A-27
10	1 hr 800 C, 1 hr 350 C, W. Q. ^(c)	538	51.8	--	12.0	--	--	5.87	1.546 ^(d)	A-32
10	1 hr 800 C, A. C.	538	49.0	--	47.0	--	--	4.52	0.963 ^(d)	A-32
10	1 hr 800 C, A. C.	538	48.7	--	54.0	--	--	4.78	0.992 ^(d)	A-32
10	--	575	55.0	54.8	1.3	4.6	--	--	--	A-5
10	--	575	55.7	55.7	1.1	5.8	--	--	--	A-5
10	--	650	36.3	34.9	1.2	18.9	--	--	--	A-5
10	--	650	34.3	31.5	1.6	21.1	--	--	--	A-5
10	--	750	17.6	17.6	0.8	20.8	--	--	--	A-5
10	--	750	17.7	16.6	0.9	18.7	--	--	--	A-5
10	--	850	10.2	8.5	2.7	16.8	--	--	--	A-5
10	--	850	10.1	7.7	4.2	16.3	--	--	--	A-5

TABLE A-14. (Continued)

Nominal Composition, w/o molybdenum	Heat Treatment and Fabrication History ^(a)	Test Temperature, C	Ultimate Tensile Strength, ksi	Yield Strength, ksi	Elongation, percent	Reduction in Area, percent	Strain Rate, in./min	Young's Modulus, 10 ⁶ psi	Poisson's Ratio	Reference
10.9	Coextruded ^(e)	100	160	--	5.6	--	--	--	--	A-28
10.9	Coextruded ^(e)	200	147	--	6.5	--	--	--	--	A-28
10.9	Coextruded ^(e)	300	128	--	4.5	--	--	--	--	A-28
10.9	Coextruded ^(e)	400	113.2	--	3.0	--	--	--	--	A-28
10.9	Cast and annealed	400	50.2	--	0.5 (in 1.2 in.)	--	--	11	--	A-28
	7 days at 900 C	600	18.8	--	0.5 (in 1.2 in.)	--	--	8.8	--	A-28
12	1 day 900 C, W. Q.	121	134	130 (0.5%)	6.5 (in 1.5 in.)	31	0.00133	--	--	A-30
12	1 day 900 C, W. Q.	221	119	113 (0.5%)	7.8 (in 1.5 in.)	32	0.00133	--	--	A-30
12	1 day 900 C, W. Q.	260	107	103 (0.5%)	7.9 (in 1.5 in.)	33	0.00133	--	--	A-30
12	1 day 900 C, W. Q.	260	104	102 (0.5%)	6.9 (in 1 in.)	50	0.005	--	--	A-29
12	1 day 900 C, W. Q.	260	119	111 (0.5%)	12.4 (in 1 in.)	39	0.033	--	--	A-30
12	1 day 900 C, W. Q.	260	110	108 (0.5%)	6.9 (in 1.5 in.)	31	0.667	--	--	A-30
12	--	288	93.6	--	11.9	22.6	--	--	--	A-30
12	1 day 900 C, W. Q.	316	99	96	6.3	23	0.00133	--	--	A-30
12	1 day 900 C, W. Q.	316	96	94 (0.5%)	8.3	30	0.033	--	--	A-30
12	1 day 900 C, W. Q.	316	105	104 (0.5%)	--	--	0.005	--	--	A-29
12	1 day 900 C, W. Q.	316	108	107 (0.5%)	3.6 (in 1 in.)	23	0.005	--	--	A-29
12	1 day 900 C, W. Q.	316	106	101 (0.5%)	4.9 (in 1 in.)	41	0.667	--	--	A-30
12	1 day 900 C, W. Q.	371	99	96 (0.5%)	4.4 (in 1.5 in.)	30	0.00133	--	--	A-30
12	1 day 900 C, W. Q.	371	102	98 (0.5%)	4.3 (in 1 in.)	33	0.005	--	--	A-29
12	1 day 900 C, W. Q.	371	97	94 (0.5%)	5.3 (in 1.5 in.)	19	0.033	--	--	A-30
12	--	691	5.47	--	--	--	--	--	--	A-31

(a) W. Q. = water quenched

A. C. = air cooled.

(b) Specimen ruptured in grips.

(c) Gamma phase may have partially transformed.

(d) Accuracy of value questionable.

(e) Low-purity starting materials.

TABLE A-15. TENSILE PROPERTIES OF γ -QUENCHED URANIUM-MOLYBDENUM ALLOYS

Molybdenum Content, w/o	γ -Quenching Medium	Tensile Strength, ksi	0.1 Percent Yield Strength, ksi	Elongation, percent	Reduction in Area, percent	Reference
7	Water	94	--	1.2	--	A-17
7.8	Water	94	--	1.2	--	A-17
10.5	Water	90	--	0.1	--	A-17
0.0	Mercury	108	29.1	3.0	8	A-33
0.6	Mercury	116	112.0	2.0	4	A-33
1.2	Mercury	190	134.0	3.0	9	A-33
2.5	Mercury	170	85.0	7.0	11	A-33
3.8	Mercury	96	40.3	12.0	13	A-33
5.2	Mercury	87	44.8	12.0	17	A-33
8.2	Mercury	148	137.0	6.0	30	A-33
9.2	Mercury	--	--	1.0	1	A-33

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SECTION B. URANIUM-NIOBIUM ALLOYS

Alloying uranium with niobium can result in stabilization of the cubic gamma phase, improved mechanical properties, and various other improvements, including corrosion resistance. Greater dilutions are required for gamma stabilization when niobium is compared with molybdenum. On the other hand, the uranium-niobium alloys are apparently not as subject to stress-corrosion effects as are uranium-molybdenum alloys.

Phase Relationships

The constitutional diagram for the niobium-uranium system is shown in Figure B-1, and isothermal transformation curves for several alloy compositions are shown in Figure B-2. Quenched structures of uranium-rich alloys, e.g. uranium-3 w/o niobium, are supersaturated and distorted forms of the orthorhombic α , whereas a quenched uranium-10 w/o niobium alloy has an ordered structure very similar to the high-temperature cubic form. Aging results in forming of the equilibrium structures after a sufficient time, i.e. α and niobium-rich γ .

Corrosion

Resistance to corrosion by water can be greatly improved by alloying uranium with niobium. A tight adherent film is formed with the alloy whereas formation of a loose oxide occurs with unalloyed uranium. Corrosion rates are compared as a function of composition and temperature in Table B-1. Note the loss of corrosion resistance by uranium-3 w/o niobium at 300 C.

Niobium alloys may be subject to stress-corrosion effects of the type suffered by uranium-molybdenum alloys; however, there has been very little systematic study of this effect.

Corrosion resistance to air is improved in niobium alloys, the rate of weight gain being 18 mg/(cm²)(hr) at 500 C for a uranium-5 w/o niobium alloy compared to 90 mg/(cm²)(hr) at 500 C for unalloyed uranium (B-1). Both materials had been gamma treated. The linear part of the weight loss curve for a uranium-0.55 w/o niobium alloy corresponded to a rate of about 0.3 mg/(cm²)(hr) in air at 150 C.

Dimensional Stability

No elongation or surface roughening resulted from the thermal cycling of uranium-0.6 w/o niobium between 100 and 500 C for 200 cycles (B-2). Greater niobium additions, which stabilize γ , should be quite satisfactory as far as dimensional stability is concerned.

Physical Properties

Thermal Expansion

The effect of composition on thermal expansion is plotted in Figure B-3.

Specific Heat

No specific heat information was available. The heat capacity of uranium-10 w/o niobium was calculated on the basis of the assumption that the law of mixtures is applicable. Values calculated in cal/(g)(C) are:

0.0278 at 0 C

0.0366 at 300 C

0.0431 at 500 C.

These estimates are no substitute for experimental data, but they do give rough approximations that are probably accurate within ± 20 percent.

Thermal Conductivity

The thermal conductivity of uranium-4 w/o niobium is plotted as a function of temperature in Figure B-4.

Density

The variation of density with composition of uranium-niobium alloys is plotted in Figure B-5.

Mechanical Properties

A wide variance in the mechanical properties of uranium-niobium alloys results primarily from the variance in phases that are present. These structures may be controlled by proper heat treating. Most of the data presented here were obtained by Jackson, et al. (B-3), using high-purity arc-cast materials. Carbon was the largest impurity noted, at 140 ppm in one case. In general, the data showed that high strength could be achieved with aging, but ductility was usually inversely proportional to strength.

Tensile Strength

The room-temperature tensile strength of gamma-treated niobium-uranium alloys is plotted in Figure B-6 as a function of composition. The relationships of tensile strength to aging temperature and test temperature for several compositions are shown in Figure B-7 and B-8.

Yield Strength

The effect of composition on the 0.2 percent offset yield strength at room temperature is shown in Figure B-9. The effect of room-temperature aging treatments on yield strength is presented in Figures B-10 and B-11. No yield strength data were available for elevated temperatures.

Ductility

Ductility as manifested by percentage elongation is plotted in Figure B-12 for different uranium-niobium compositions. The effect of a 1-hr aging treatment on ductility is plotted in Figure B-13.

Young's Modulus

Values for modulus of elasticity are plotted in Figure B-14 as a function of composition. A significant increase in Young's modulus results from aging.

Poisson's Ratio

No values for Poisson's ratio were found in the literature.

Discussion

Stress-corrosion studies on uranium-niobium alloys are needed in order to assess the susceptibility of these alloys to delayed-cracking phenomena. Specific heat, Poisson's ratio, Young's modulus, and yield strength at elevated temperatures also need to be determined.

FIGURE B-1. PHASE DIAGRAM OF THE SYSTEM NIOBIUM-URANIUM^(B-4, B-5, B-6)

FIGURE B-2. ISOTHERMAL TRANSFORMATIONS OF URANIUM-NIOBIUM ALLOYS^(B-7)

FIGURE B-3. EFFECT OF INCREASING NIOBIUM ADDITION ON THERMAL-EXPANSION COEFFICIENT AT ROOM TEMPERATURE^(B-8)

FIGURE B-4. EFFECT OF TEMPERATURE ON THERMAL CONDUCTIVITY OF URANIUM-4 w/o NIOBIUM^(B-9)

B-6

FIGURE B-5. EFFECT OF NIOBIUM ADDITION ON DENSITY OF URANIUM-NIOBIUM ALLOYS^(B-10)

FIGURE B-6. EFFECT OF NIOBIUM ADDITION ON ULTIMATE TENSILE STRENGTH AT ROOM TEMPERATURE^(B-11)

FIGURE B-7. EFFECT OF AGING TEMPERATURE ON THE ULTIMATE TENSILE STRENGTH OF SEVERAL URANIUM-NIOBIUM ALLOYS AT ROOM TEMPERATURE AND A STRAIN RATE OF 0.002 IN./IN./MIN(B-3)

FIGURE B-8. EFFECT OF INCREASING TEMPERATURE ON THE ULTIMATE TENSILE STRENGTH OF URANIUM-6.4 w/o NIOBIUM AT A STRAIN RATE OF 0.002 IN./IN./MIN(B-3)

FIGURE B-9. EFFECT OF NIOBIUM ADDITION AND AGING TREATMENT ON THE YIELD STRENGTH AT ROOM TEMPERATURE (B-3)

FIGURE B-10. EFFECT OF AGING TEMPERATURE ON THE 0.2 PERCENT OFFSET YIELD STRENGTH OF SEVERAL URANIUM-NIOBIUM ALLOYS AT ROOM TEMPERATURE AND A STRAIN RATE OF 0.002 IN./IN./MIN (B-3)

FIGURE B-11. EFFECT OF AGING TIME AT 150 C ON THE YIELD STRENGTH OF URANIUM-6.4 w/o NIOBIUM AT ROOM TEMPERATURE^(B-3)

The material was initially water quenched from 850 C. The strain rate was 0.002 in./in./min.

FIGURE B-12. EFFECT OF NIOBIUM ADDITION ON ELONGATION AT ROOM TEMPERATURE^(B-11)

FIGURE B-13. EFFECT OF AGING FOR 1 HR AT VARIOUS TEMPERATURES ON THE ELONGATION OF SEVERAL URANIUM-NIOBIUM ALLOYS AT ROOM TEMPERATURE^(B-3)

FIGURE B-14. EFFECT OF NIOBIUM ADDITION ON YOUNG'S MODULUS AT ROOM TEMPERATURE^(B-3)

The uranium-niobium alloys were arc cast and hot rolled prior to the heat treatment indicated. The strain rate was 0.002 in./in./min.

TABLE B-1. CORROSION RATES OF SEVERAL
URANIUM-NIOBIUM ALLOYS IN
WATER

Nominal Composition, w/o niobium	Prior Heat Treatment(a)	Test Temperature, C	Average Rate of Weight Change, mg/(cm ²)(hr)	Reference
0	2 hr at 900 C + W.Q.	100	-0.78	B-12
1.59	1 hr at 815 C + W.Q.	316	+0.0004	B-12
1.59	4 hr at 615 C + F.C.	316	-2.4	B-12
3	γ -quenched	100	$\sim +0.0004$	B-13
3	γ -quenched + 24 hr at 350 C	100	$\sim +0.0004$	B-13
3	γ -quenched	300	-0.7	B-14
6	2 hr at 850 C + W.Q.	100	+0.0005	B-12

(a) W.Q. = water quenched.

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SECTION C. URANIUM-ZIRCONIUM ALLOYS

Uranium-zirconium alloys can be readily fabricated, are corrosion resistant, and offer strengthening advantages over unalloyed uranium. Furthermore, dimensional stability is excellent, with respect to thermal cycling in the α -phase region.

Phase Relationships

The uranium-zirconium phase diagram is shown in Figure C-1. Isothermal transformation diagrams are shown in Figures C-2 and C-3. As may be seen, this system, like the niobium-uranium system, is characterized by a complete series of solid solutions between the body-centered-cubic forms of uranium and zirconium, gamma phase. Unlike niobium, however, it is not possible to retain gamma at room temperature with high uranium contents, and these alloys are primarily of the α -phase type.

Corrosion

Numerous studies of the corrosion resistance of uranium-zirconium alloys to water, and also CO_2 and air, have been performed (C-1 through C-5). The alloy must be quenched for corrosion resistance to water. Corrosion rates in water are plotted in Figure C-4 and, as may be seen, a 10 w/o addition of zirconium is very effective in suppressing corrosion. Slow cooling results in a tendency for forming the equilibrium $\alpha + \delta$ structures, this α being very similar to unalloyed uranium. Quenching from γ , on the other hand, leads to the forming of a martensitic type of alpha, α , supersaturated with zirconium.

The rates of corrosion of various alloys at temperatures of 500 C or greater in air and CO_2 are tabulated in Table C-1. By way of comparison, the rate of weight loss in air at 150 C was 0.05 and 0.2 mg/(cm²)(hr) for alloys containing 2 and 1 w/o zirconium, respectively (C-4). These latter alloys had been gamma quenched.

It can be concluded from these oxidation data at temperatures of 150 to 1000 C, that resistance to oxidation at 150 C can result from alloying. At the higher temperatures both alloyed and unalloyed uranium have poor oxidation properties, but some improvement does result from alloying.

Dimensional Stability

No improvement in thermal cycling behavior (compared to unalloyed uranium) results with α -rolled zirconium-uranium alloys that contain up to 5.4 w/o zirconium (C-6). Elongation on the order of 15 percent resulted in these alloys after 700 cycles between 100 and 500 C.

Heat-treated zirconium alloys, on the other hand, are significantly better than beta-treated uranium. This improvement is realized in dimensional change and surface roughening. Thus, the elongation of uranium-2.2 w/o zirconium that had been γ annealed plus α annealed was +0.1 percent compared to -1.44 percent for β -quenched and α -annealed uranium after 500 cycles between 100 and 500 C (C-7). Although surface-roughening effects are present with low zirconium additions, additions of 2 w/o or more essentially eliminate roughening and dimensional changes after 1000 cycles between 100 and 500 C. The optimum heat treatment for the alloys studied (0.1 to 5.4 w/o zirconium) was found to consist of γ quenching from 800 C down to 500 to 575 C, and isothermally decomposing at the lower temperature (C-6).

Physical Properties

Thermal Expansion

Thermal expansion coefficients for various uranium-zirconium alloys are plotted in Figure C-5. The 800-670 C heat treatment is essentially a gamma plus beta treatment. The 800-780-550 C heat-treating schedule is an alpha transformation treatment from gamma. Both treatments minimize preferred orientation effects.

Specific Heat

The specific heat characteristics of uranium-5.4 w/o zirconium have recently been studied by the Russians (C-8). A pulsed heating method employing an electric current through the test specimen was used in obtaining the data. Their results are shown in Figure C-6. The discontinuities probably result from phase transformation, in agreement with the effect of phase transformation on the specific heat of unalloyed uranium. Equations relating the specific heat in kcal/(g-at)(C) with temperature for the above alloy and for unalloyed uranium by the same investigators are:

α -uranium up to 650 C

$$C_p = 2.69 + 9.698 \times 10^{-3} T + 1.072 \times 10^{-5} T^2$$

Uranium-5.4 w/o zirconium to 600 C

$$C_p = 3.56 \times 10^{-1} + 1.425 \times 10^{-2} T + 2.59 \times 10^{-5} T^2.$$

Thermal Conductivity

A plot of thermal conductivity as a function of zirconium content is given in Figure C-7 for various temperatures.

Density

The density of zirconium-uranium alloys at room temperature is shown in Figure C-8.

Mechanical Properties

Most of the mechanical properties data were obtained with alloys that had been prepared by arc melting in water-cooled copper crucibles or induction melting in graphite crucibles. The former process was characterized by higher purities. Strain rates used in tensile testing were ≈ 0.003 in./in./min, except as specified.

Tensile Strength

The effects of zirconium addition, temperature, and fabrication history on tensile strength are shown in Figure C-9. Strength increases with increasing amount of alloy. Additional information on the effect of strain rate and other variables is given in Table C-2 for high-purity arc-cast compositions. Strength increased with strain rate.

Yield Strength

Yield strength as a function of composition is plotted in Figure C-10. The effects of temperature and fabrication history are also shown. Strengthening is proportional to the amount of alloying addition. Additional information is given in Table C-2 on the effects of several variables.

Ductility

The variation of ductility with zirconium addition, fabrication history, strain rate, etc. is plotted in Figure C-11 and tabulated in Table C-2.

Young's Modulus

Values of Young's modulus are plotted in Figure C-12 as a function of temperature, composition, and fabrication history.

Poisson's Ratio

No values of Poisson's ratio were found in this survey.

Discussion

The possibility of delayed cracking effects occurring with uranium-zirconium alloys should be investigated. Detailed studies of the effect of aging and strain rate on mechanical properties are lacking for uranium-zirconium alloys. Poisson's-ratio determinations are also required for this system.

FIGURE C-1. URANIUM-ZIRCONIUM CONSTITUTIONAL DIAGRAM^(C-9)

FIGURE C-2. TIME-TEMPERATURE-TRANSFORMATION DIAGRAM OF URANIUM-2 w/o ZIRCONIUM^(C-10)

FIGURE C-3. TIME-TEMPERATURE-TRANSFORMATION DIAGRAM FOR URANIUM-6 w/o ZIRCONIUM^(C-11)

FIGURE C-4. CORROSION RATES OF ZIRCONIUM-URANIUM ALLOYS IN 100 C (212 F) WATER(C-11)

FIGURE C-5. EFFECT OF ZIRCONIUM ADDITION ON THE THERMAL EXPANSION COEFFICIENT BETWEEN 20 AND 400 C(C-12)

C-8

FIGURE C-6. SPECIFIC HEAT OF URANIUM-5.4 w/o ZIRCONIUM AS A FUNCTION OF TEMPERATURE(C-8)

FIGURE C-7. EFFECT OF ZIRCONIUM ADDITION AT SEVERAL TEMPERATURES ON THERMAL CONDUCTIVITY(C-1)

FIGURE C-8. DENSITY OF ZIRCONIUM-URANIUM ALLOYS(C-13 through C-16)

FIGURE C-9. EFFECT OF ZIRCONIUM ADDITION ON ULTIMATE TENSILE STRENGTH AT ROOM TEMPERATURE AND 370 C(C-1)

The alloys were gamma rolled and alpha annealed for 24 hr at 575 C.

FIGURE C-10. EFFECT OF ZIRCONIUM ADDITION ON 0.2 PERCENT YIELD STRENGTH AT ROOM TEMPERATURE AND 370 C(C-1)

The alloys were gamma rolled and alpha annealed for 24 hr at 575 C.

FIGURE C-11. EFFECT OF ZIRCONIUM ADDITION ON ELONGATION AT ROOM TEMPERATURE AND 370 C(C-1)

The alloys were gamma rolled and alpha annealed for 24 hr at 575 C.

FIGURE C-12. EFFECT OF INCREASING TEMPERATURE ON MODULUS OF ELASTICITY OF SEVERAL URANIUM-ZIRCONIUM ALLOYS THAT HAD BEEN GAMMA ROLLED AND ALPHA ANNEALED FOR 24 HR AT 575 C(C-1)

TABLE C-1. CORROSION RATES OF URANIUM-ZIRCONIUM ALLOYS IN HIGH-TEMPERATURE CO₂ AND AIR^(C-5)

Nominal Composition, w/o zirconium	Exposure Temperature, C	Rate of Weight Gain, mg/(cm ²)(hr)
<u>CO₂</u>		
0	500	0.1 - 0.3
0	680	3 - 10
0	800	250 - 330
0	1000	≤100
3	500	0.05
3	680	53
3	800	340
3	900	180
6	500	0.23
6	680	25
6	800	400
6	900	180
10	500	0.2
10	680	26
10	800	400
10	900	230
<u>Air</u>		
0	500	90
3	500	80
6	500	70
10	500	45

TABLE C-2. EFFECT OF ZIRCONIUM ADDITION, TEST TEMPERATURES,
HEAT TREATMENT, AND STRAIN RATE ON THE TENSILE
PROPERTIES OF URANIUM-ZIRCONIUM ALLOYS^(C-17)

Nominal Composition, w/o zirconium	Heat Treatment ^(a)	Test Temperature, C	Young's Modulus, 10 ⁶ psi	Ultimate Tensile Strength, ksi	0.2 Percent Yield Strength, ksi	Elongation, percent	Strain Rate, in./in./min
0	1 hr at 800 C + W.Q.	Room	22 - 28	110.0	35.0	25.0	0.05
0	Ditto	600	--	6.3	--	43.0	0.001
0	"	600	--	8.4	--	36.0	0.01
0	"	600	--	8.9	--	57.0	0.1
5	"	Room	19.0	234.0	170.0	5.0	0.05
5	1 hr at 800 C + W.Q. + 8 hr at 500 C	Room	--	190.0	130.0	7.0	0.05

(a) W. Q. = water quenched.

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C-15 and C-16

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SECTION D. URANIUM-CHROMIUM ALLOYS

A minor chromium addition to uranium can result in significant improvements in fuel-element performance and fabrication. Uranium-rich compositions are α -phase alloys with chromium present as the second phase. It is possible to retain the β phase in metastable equilibrium at low temperatures, but only for short times and over a small range of compositions. Very limited studies have been performed on these alloys when compared with studies on the other alloys in this survey. The uranium-chromium alloys can be readily cast to shape and may provide advantages for replaceable sections within the reactor core.

Phase Relationships

The uranium-chromium system is one of the few systems that form a eutectic without any intermetallic phases. The phase diagram is shown in Figure D-1. Isothermal transformation curves for retention of the β phase are shown in Figure D-2.

Corrosion

No information on the corrosion resistance of these alloys was found.

Dimensional Stability

The effect of thermal cycling in the α stability range on dilute uranium alloys is compared with effects on alloyed uranium in Table D-1. A significant improvement is apparent, although data are limited.

Physical PropertiesThermal Expansion

Average thermal expansion coefficients for uranium-0.1 w/o chromium are^(D-1):

12.68 x 10⁻⁶ per C from 40 to 50 C

14.83 x 10⁻⁶ per C from 40 to 50 C.

Values for uranium ~0.4 w/o chromium are^(D-1):

12.41×10^{-6} per C from 40 to 50 C

15.00×10^{-6} per C from 40 to 50 C.

Specific Heat

The specific heat of uranium-5.6 w/o chromium is plotted as a function of temperature in Figure D-3.

Thermal Conductivity

The variation of thermal conductivity as a function of temperature is plotted for two uranium alloys in Figure D-4. The addition of chromium serves to increase the conductivity.

Density

The available densities of various uranium-chromium alloys are listed in Table D-2.

Mechanical Properties

Most of the mechanical-property data for this alloy system were classified; therefore, all this information is given in the classified supplement.

Discussion

Very little study of uranium-chromium alloys has been performed, compared with other alloys. The information that is available is usually limited with respect to the effect of variable composition. No corrosion information was available.

FIGURE D-1. THE URANIUM-CHROMIUM CONSTITUTIONAL DIAGRAM^(D-2)

FIGURE D-2. TEMPERATURE VERSUS TRANSFORMATION-TIME CURVES FOR URANIUM-CHROMIUM ALLOYS^(D-3)

FIGURE D-3. EFFECT OF TEMPERATURE ON SPECIFIC HEAT OF URANIUM-5.6 w/o CHROMIUM^(D-4)

FIGURE D-4. EFFECT OF TEMPERATURE ON THE THERMAL CONDUCTIVITY OF TWO URANIUM-CHROMIUM ALLOYS^(D-4)

TABLE D-1. EFFECT OF 500 THERMAL CYCLES BETWEEN 100 AND 500 C ON β -QUENCHED AND α -ANNEALED URANIUM-CHROMIUM ALLOYS (D-3)

Chromium Addition, w/o	Total Length Change, percent	Surface Condition
0	-1.44	Warped and bumped
0.1	-0.07	Good
0.42	-0.086	Good

TABLE D-2. DENSITIES OF VARIOUS URANIUM-CHROMIUM ALLOYS

Composition, w/o chromium	Density, g per cm ³	Reference
0.30	18.697	D-5
0.59	18.697	D-5
5.0	17.56	D-4
5.27	17.44	D-4
5.42	17.41	D-4
5.60	17.57	D-4
5.92	17.26	D-4

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SECTION E. URANIUM-7.5 w/o NIOBIUM-2.5 w/o ZIRCONIUM
(MULBERRY ALLOY)

Mulberry alloy combines niobium and zirconium alloying additions to uranium to yield a material that possesses many desirable properties. The high-temperature gamma phase can be retained by quenching, and aging can greatly strengthen this alloy. Although originally thought to be immune to the stress-corrosion attack that uranium-molybdenum alloys are subject to, this advantage is not too firm in the light of present information.

Phase Relationships

Phase relationships in the uranium-niobium-zirconium system have been investigated by Dwight and Mueller^(E-1). An isothermal section of the ternary system is shown in Figure E-1. A vertical section through the constitutional space model at 7 w/o niobium is shown in Figure E-2. Time-temperature-transformation relationships have not been fully defined, but some information is shown in Figure E-3. Gamma phase is retained by quenching. The equilibrium structure below about 630 C is $\alpha + \gamma$. The exact form and composition of α and γ are dependent on heat treatment, and can vary considerably.

Corrosion

In a study at LRL, Peterson and Vandervoort originally reported that Mulberry alloy was immune to the stress-corrosion effects noted with uranium-10 w/o molybdenum alloys^(E-2, E-3). The basis for this finding was a lack of premature cracking in tensile specimens loaded under stresses of 100 ksi in air of unspecified humidity. Peterson and Steele later found that the alloy could be susceptible to stress-corrosion cracking in humid air (90 percent relative humidity), but not with dry air (40 percent relative humidity)^(E-4). In these studies, tensile specimens in various conditions were stressed at a constant load level, 86 to 120 percent of the yield strength, in wet or dry air. Results are summarized in Table E-1. In addition, tensile tests under varying strain rates were performed on specimens with similar fabrication histories. Findings were that brittle failures could occur in the humid air if surface stress risers or oxidation were present. If the surface was freed of these effects by machining, or if stresses were reduced by annealing at 150 C, susceptibility to brittle fracture was reduced or eliminated at loads up to 100 percent of the 0.2 percent offset yield strength (see Table E-2), as manifested in the tensile ductility measurements. The specific corroding agent responsible for this stress-corrosion phenomenon has not been identified, although moisture is suspected. This contrasts with the finding that oxygen was responsible for stress corrosion of uranium-molybdenum alloys. Irregardless of the exact mechanisms involved, Mulberry alloy does represent a substantial improvement over uranium-10 w/o molybdenum with respect to the degree of susceptibility to stress corrosion, since stress levels of 30 percent of the yield strength can lead to failure with the molybdenum alloy, whereas stresses of 90 percent of the yield strength, ≈ 100 ksi, are necessary with Mulberry alloy.

Dimensional Stability

Mulberry alloy is not subject to thermal ratcheting when tested in the γ or γ plus α_2 condition(E-5). The term " α_2 " probably refers to a nonequilibrium form of α .

Physical Properties

Thermal Expansion

Average thermal expansion coefficients for Mulberry alloy are given in Table E-3. High-purity materials, arc cast in water-cooled copper, were used in these studies. A typical interstitial analysis was 100 ppm carbon, 35 ppm oxygen, 14 ppm nitrogen, and 18 ppm hydrogen. Irregularities in expansion and contraction occurred in the temperature range 380 to 650 C, presumably due to phase transformation(E-2).

Specific Heat

Tentative values for the specific heat of Mulberry alloy at various temperatures are given in Table E-4. Parker's values(E-6) were obtained using a condenser-bank discharge technique to provide for a very high rate of heat input, whereas Lagedrost(E-7) used conventional techniques wherein the specimen was dropped into an ice bath from temperature. The difference in technique could account for the discrepancy. Lagedrost obtained erratic enthalpy values in the temperature range 300 to 700 C. These could have resulted from the phase transformation that would occur below about 600 C from the original γ to γ plus α phases. Crystal structure will be determined in a current Battelle program designed to determine accurate specific heat values. Until these results become available, it is advisable to consider the values of specific heat to lie in the scatter band given by the values in Table E-4.

Thermal Conductivity

The relationship of thermal conductivity to temperature is plotted for Mulberry alloy in Figure E-4.

Density

The room-temperature density of cast Mulberry alloy is 16.4 g per cm³ in the as-cast condition, and 16.6 g per cm³ in the wrought condition(E-2).

Mechanical Properties

Mechanical properties were generally obtained at LRL on high-purity materials made from ingots that had been prepared by arc-melting techniques. A typical interstitial analysis was 100 ppm carbon, 35 ppm oxygen, 14 ppm nitrogen, and 18 ppm hydrogen.

Tensile Strength

The tensile strength of gamma-phase Mulberry alloy is plotted in Figure E-5 as a function of strain rate for various temperatures. An equation that relates tensile strength with strain rate, as based on these curves, is

$$\dot{\epsilon} = D \left[\frac{UTS - UTS_o}{UTS_o} \right]^P$$

where $\dot{\epsilon}$ = strain rate in min^{-1} , D = strain rate coefficient in min^{-1} , P = dimensionless exponent, UTS_o = ultimate tensile strength, in ksi, at $\dot{\epsilon} = 0.0012 \text{ min}^{-1}$, and UTS = ultimate tensile strength at the desired strain rate. Values of these constants are tabulated below:

Temperature, C	P	D x 10 ⁻³
23	5.7	710
200	9.5	52,400
300	7.3	1,400
400	7.4	164
500	7.2	0.66

The variance in room-temperature tensile strength as a function of production-type variables for γ -phase material is given in Table E-2. The last treatment is probably optimum with respect to resistance to stress corrosion. The effect of aging on the tensile properties of the alloy is given in Table E-5. The low-temperature anneals resulted in strengthening associated with various stages of transformation and overaging at the higher aging temperatures.

Yield Strength

The yield strength of Mulberry alloy for various conditions of fabrication is given in Tables E-2 and E-5. The effect of temperature on the yield strength is given in Table E-6.

Ductility

The room-temperature values of ductility, as indicated by tensile elongation and reduction in area, for various heat treatments are tabulated in Tables E-2 and E-5. Ductility is greatest in the γ -quenched condition, and least after aging at low temperatures. Strain rate has a minor effect on ductility (as measured by reduction in area), as shown in Figure E-6. The effect of test temperature on ductility is given in Table E-6.

Young's Modulus

Values of Young's modulus as a function of test temperature are plotted in Figure E-7.

Poisson's Ratio

Values of Poisson's ratio, as determined ultrasonically, are plotted in Figure E-7. Structures were probably $\alpha + \gamma$ at the higher temperatures.

Discussion

A good deal of pertinent research has been performed on Mulberry alloy of high purity and quality, but because this ternary alloy is extremely complex, there are a lot of gaps in the information that is available. Information on phase equilibrium and phase transformation is incomplete. The delayed-cracking phenomenon is not fully understood. The relationship of physical properties, especially specific heat, with crystal structure has not been determined in any detail. Mechanical properties, including Young's modulus, should be determined at high temperatures as a function of preaging treatments.

FIGURE E-1. PARTIAL PHASE RELATIONSHIPS IN THE SYSTEM URANIUM-NIOBIUM-ZIRCONIUM AT 600 C (E-1)

FIGURE E-2. VERTICAL SECTION AT 7 w/o NIOBIUM, VARIABLE ZIRCONIUM, BALANCE URANIUM^(E-1)

FIGURE E-3. TIME-TEMPERATURE-TRANSFORMATION (TTT) CURVES FOR GAMMA-PHASE URANIUM-7.5 w/o NIOBIUM-2.5 w/o ZIRCONIUM ALLOY(E-3)

The hardness curve is considered the more accurate.

FIGURE E-4. EFFECT OF TEMPERATURE ON THE THERMAL CONDUCTIVITY OF MULBERRY ALLOY(E-8)

FIGURE E-5. EFFECT OF STRAIN RATE ON THE TENSILE STRENGTH OF MULBERRY ALLOY AT VARIOUS TEMPERATURES^(E-5)

Specimens were made from 1/2-in. plate that had been heat treated at 800 C for 20 min, water quenched, and then aged for 1 hr at 150 C.

FIGURE E-6. EFFECT OF STRAIN RATE ON DUCTILITY (REDUCTION IN AREA) OF MULBERRY ALLOY AT VARIOUS TEMPERATURES^(E-5)

Specimens were made from 1/2-in. plate that had been heat treated at 800 C for 20 min, water quenched, and then aged for 1 hr at 150 C.

FIGURE E-7. EFFECT OF TEMPERATURE ON VARIOUS MECHANICAL PROPERTIES OF GAMMA-PHASE URANIUM-7.5 w/o NIOBIUM-2.5 w/o ZIRCONIUM ALLOY (E-5)

TABLE E-1. RESULTS OF CONSTANT-LOAD TESTS ON
MULBERRY ALLOY(E-4)

Specimen	Condition of Specimen	Load Stress, percent of yield strength	Environment ^(a)	Remarks
9	As received	86 to 100	Dry	No failure in 500 hr
2	As received	86 to 100	Wet	No failure in 500 hr
7	1. Machined 2. 900 C, 1 hr 3. Water quenched 4. 150 C, 1 hr	90	Dry	No failure in 140 hr
12	1. Machined 2. 900 C, 1 hr 3. Water quenched	90	Wet	Failed in 0.44 hr ^(b)
31	1. 900 C, 1 hr 2. Water quenched 3. Machined	90 to 100	Dry	No failure in 200 hr
15	1. 900 C, 1 hr 2. Water quenched 3. Machined	110	Dry	Failed in 5 min ^(c)
25	1. 900 C, 1 hr 2. Water quenched 3. Machined	100 to 110	Wet	Failed in 120 hr ^(c)
20	1. 900 C, 1 hr 2. Oil quenched 3. Machined	90 to 100	Dry	No failure in 300 hr
26	1. 900 C, 1 hr 2. Oil quenched 3. Machined	110 to 120	Wet	Failed in 161 hr ^(c)
4	1. Machined 2. 900 C, 1 hr 3. Oil quenched	90 to 110	Dry	No failure in 300 hr
10	1. Machined 2. 900 C, 1 hr 3. Oil quenched	100	Wet	Failed in 7 hr ^(b)
23	1. Machined 2. 900 C, 1 hr 3. Water quenched 4. 150 C, 1 hr	90	Wet	Failed in 0.74 hr ^(b)

TABLE E-1. (Continued)

Specimen	Condition of Specimen	Load Stress, percent of yield strength	Environment ^(a)	Remarks
33	1. Machined 2. 900 C, 1 hr 3. Water quenched 4. 150 C, 1 hr	90	Wet	Failed in 0.50 hr ^(b)
32	1. 900 C, 1 hr 2. Water quenched 3. 150 C, 1 hr 4. Machined	90 to 100	Dry	No failure in 300 hr
24	1. 900 C, 1 hr 2. Water quenched 3. 150 C, 1 hr 4. Machined	90 to 100	Wet	No failure in 300 hr

(a) Wet: air at 90 to 95 percent relative humidity
 Dry: air at 40 percent relative humidity.

(b) Failure initiated at scratch or root of thread.

(c) Failure in ductile tension due to overload.

TABLE E-2. TENSILE PROPERTIES^(a) OF MULBERRY ALLOY AS
A FUNCTION OF HEAT TREATMENT(E-2)

Condition of Specimen	0.2 Percent Offset Yield Strength, psi	Ultimate Tensile Strength, psi	Elongation in 1 In., percent	Reduction in Area, percent
As received	120,000	139,800	19	56
1. 900 C, 1 hr	117,000	137,000	21	61
2. Water quenched				
3. Machined				
1. Machined	117,000	137,000	20	60
2. 900 C, 1 hr				
3. Water quenched				
1. Machined	117,000	137,000	19	61
2. 900 C, 1 hr				
3. Oil quenched				
1. 900 C, 1 hr	105,200	133,000	24	63
2. Oil quenched				
3. Machined				
1. Machined	118,000	138,000	20	56
2. 900 C, 1 hr				
3. Water quenched				
4. 150 C, 1 hr	100,000	129,000	22.5	58
1. 900 C, 1 hr				
2. Water quenched				
3. 150 C, 1 hr				
4. Machined				

(a) Temperature of tensile test, 22 C
Area of cross section, 0.01227 in.²
Strain rate, 0.05 in./in./min.

TABLE E-3. AVERAGE THERMAL EXPANSION COEFFICIENTS FOR MULBERRY ALLOY(E-2)

Temperature Range, C	Coefficient of Expansion, 10 ⁻⁶ per C
20 - 300	14.8
640 - 1000	14.4
20 - 1000	16.9

TABLE E-4. SPECIFIC HEAT OF MULBERRY ALLOY

Temperature, C	Specific Heat Determined by Indicated Source, cal/(g)(C)	
	Parker(E-6)	Lagedrost(E-7)
25	0.035	0.034
200	0.039	0.037
300	0.042	0.038
450	0.045	-
575	0.050	-
700	-	0.043
800	-	0.044

TABLE E-5. THE EFFECT OF AGING ON THE ROOM-TEMPERATURE TENSILE PROPERTIES OF MULBERRY ALLOY AT A STRAIN RATE OF 0.05 IN./IN./MIN(E-2)

Material Condition(a)	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 In., percent	Reduction in Area, percent
1 hr at 900 C, W.Q., 1 hr at 600 C	163.6	66.5	13.0	41
1 hr at 900 C, W.Q., 1 hr at 500 C	177.0	77.0	9.5	33
1 hr at 900 C, W.Q., 1 hr at 400 C	219.0	210.0	1.0	1.3
1 hr at 900 C, W.Q., 1 hr at 350 C	225.0	220.0	1.0	0.5

(a) W.Q. = water quenched.

TABLE E-6. ELEVATED-TEMPERATURE TENSILE PROPERTIES OF
MULBERRY ALLOY AT A STRAIN RATE OF 6.0 IN. /
IN. / MIN^(E-2)

Test Temperature, C	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 1 In., percent	Reduction in Area, percent
Room	111.0	101.0	(a)	42
150	90.3	71.2	20	39
250	84.8	69.4	14	38
350	78.3	71.4	10	36
450	59.6	53.8	8	44
550	41.0	37.6	12	52
650	26.0	24.1	19	59
750	18.9	18.8	29	60
850	15.0	14.1	40	74
950	10.3	(b)	60	85

(a) Broke outside gage length.

(b) Yield load is questionable.

References

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