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ALLOYS OF URANIUM WITH
ZIRCONIUM, CHROMIUM, COLUMBIUM
VANADIUM, AND MOLYBDENUM

by

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TABLE OF CONTENTS

	<u>Page</u>
INTRODUCTION	9
ZIRCONIUM-URANIUM ALLOYS	9
Equilibrium Diagram	9
Cladding and Diffusion	11
Roll Cladding	11
Extrusion Cladding	12
Diffusion	12
Properties	12
CHROMIUM-URANIUM ALLOYS	14
The Equilibrium Diagram	14
Properties	17
COLUMBIUM-URANIUM ALLOYS	17
Equilibrium Diagram	17
Diffusion	20
Properties	20
VANADIUM-URANIUM ALLOYS	23
The Equilibrium Diagram	23
Properties	23
MOLYBDENUM-URANIUM ALLOYS	28
The Equilibrium Diagram	28
Properties	30
Diffusion	33
BIBLIOGRAPHY	39

ABSTRACT

Information on five uranium binary alloy systems has been surveyed. These systems are the alloys of uranium with zirconium, chromium, columbium, vanadium, and molybdenum. The equilibrium diagrams are discussed, and where available, data have been included on diffusion studies, cladding experiments, and mechanical properties.

INTRODUCTION

Current interest in alloying uranium to improve the corrosion resistance and dimensional stability of fuel elements and slugs has prompted this survey of some of the more promising alloying elements. The binary systems of uranium with five such important elements have been surveyed. The objective was primarily to obtain information on the phase equilibria which might be expected in using these materials. Information was also included on related subjects such as diffusion, cladding, and mechanical properties.

Some of the data are controversial, hence, it was impossible to present positive results in all cases. In general, both sides of controversial issues have been discussed and while some attempt has been made to analyze the results, this was not usually necessary. It is expected that future work may not only produce refinement, but in some cases correction of the surveyed information.

ZIRCONIUM-URANIUM ALLOYS

Equilibrium Diagram

A tentative zirconium-uranium equilibrium diagram was presented at the AEC Metallurgical Conference in 1950.⁽¹⁾ The basic diagram presented at that time is shown in Figure 1 with subsequent revision. The early work indicated that beta zirconium and gamma uranium were completely intersoluble and that beta zirconium could not be retained by quenching alloys of 11 atomic per cent uranium (25 weight per cent). These features were generally confirmed by Ames investigators,⁽²⁾ however, they were unable to find the intermediate phase which MIT⁽³⁾ reports exists from about 17 to 48 atomic per cent uranium (35 to 70 weight per cent). This range of solubility is based on a slightly changing structure as observed by X-ray diffraction. The presence of the compound was further confirmed by observations of alpha uranium-plus-epsilon in high-uranium alloys and alpha zirconium-plus-epsilon in high-zirconium alloys.⁽³⁾ Tentative-metallographic observations seem to confirm these data.⁽³⁾ Examination of diffusion couples of zirconium-uranium at Battelle also tend to confirm the presence of an intermediate phase in the system.

The melting points of zirconium-uranium alloys were reported by Ames⁽²⁾ for alloys of 4 to 66 atomic per cent uranium. These data were reported as single-temperature values and show an approximate linear relationship in accordance with the solidus-liquidus of Figure 1.

FIGURE 1. ZIRCONIUM - URANIUM CONSTITUTIONAL DIAGRAM

The solubility of uranium in alpha zirconium has been reported by a number of cooperating laboratories. Westinghouse⁽⁴⁾ studied the alloys by dilatation. They extrapolated a plot of the "eutectoid-transformation dilatation" for a series of alloys and obtained zero dilatation at 0.3 atomic per cent uranium (0.8 weight per cent). Similarly, MIT⁽³⁾ has observed dilatation effects in alloys containing as little as 0.5 atomic per cent (1.5 weight per cent). X-ray diffraction studies showed lattice changes up to 0.8 atomic per cent (2.0 weight per cent) uranium. The lattice was unchanged at higher compositions, and at 1.6 atomic per cent (4.0 weight per cent) the (123) line of beta zirconium was observed for all conditions of treatment.⁽⁵⁾ It seems likely then that the maximum solubility in alpha zirconium is about 0.3 atomic per cent uranium and certainly no higher than 0.8 atomic per cent.

The U_B -plus- $(U_\gamma-Zr_B)$ region extends to about 18⁽⁶⁾ or 21⁽²⁾ atomic per cent zirconium, Figure 1. The solubility in the beta uranium appears to be limited, but needs further study. At about 685 C^(2,3) alpha uranium is formed by a peritectoid reaction. The "room-temperature" solubility in alpha uranium has been reported as less than 1.5 atomic per cent (0.57 weight per cent),⁽²⁾ the maximum solubility has been observed tentatively as high as five or six atomic per cent.^(3,6) These values should also be clarified by further work.

Cladding and Diffusion

Roll Cladding

The successful cladding of uranium with zirconium has been accomplished by a number of experimenters. Beaver⁽⁷⁾ recently reported on roll cladding of zirconium-uranium-zirconium sandwiches which were sealed off in evacuated steel packs and rolled at 635 C (1175 F). Metallurgical or alloy bonds were reported for this work. Bond tensile strengths of 48,300 and 60,500 pounds per square inch were obtained with surface-increase ratios of 8 to 1 and 14 to 1, respectively. Attempts to roll at 954 C (1750 F) produced rough contours of the clad product. This also is an unsafe temperature for rolling of zirconium in iron jackets, because of the proximity of the zirconium-iron eutectic reaction. Somewhat similar results were previously reported by both Battelle and Argonne. In the Argonne⁽⁸⁾ experiment, a dynamically evacuated pack containing a zirconium-uranium-zirconium sandwich was heated at 650 C. When outgassing was complete, the pack was sealed off and rolled to 1/4-inch thickness in five 25 per cent reduction passes. The pack was reheated to 650 C after each pass through the mill. The resulting clad sandwich appeared sound by metallographic examination. Further improvement was obtained by two- and six-hour diffusion anneals at 1000 C.

Keeler⁽⁹⁾ of Battelle, successfully clad a zirconium-0.006-inch uranium-zirconium sandwich by welding off in a steel pack, and rolling to a 3 to 1 reduction at 900 C (1650 F). The sandwich appeared to have an alloy bond and was further improved by 20 hours at 1800 F in vacuo. Annealing at 2000 and 2200 F produced extensive diffusion, essentially eliminating the high-uranium phase from the center of the sandwich.

Extrusion Cladding

MIT reported on extrusion cladding of uranium with zirconium at the 1952 Metallurgical Conference.⁽¹⁰⁾ Successful bonding and cladding were obtained in two temperature ranges: the low alpha, about 500 C; and high alpha, about 630 C. Small-scale 3/8-inch rods were extruded with a 0.020-inch cladding of zirconium. Variations of 0.005 inch on the radius of the clad surface were obtained "without special precautions". The material extruded at low-alpha temperatures was fine grained, but was severely oriented. The high-alpha extruded rod exhibited little preferred orientation and was coarse grained. It was suggested during the ensuing discussion that this may have been the result of extruding in the beta-temperature range. However, it was the opinion of the author⁽¹⁰⁾ that this was not the case.

Extrusion in copper cans resulted in considerable ridging of the final product. Less ridging was obtained when an iron can was used, and was readily overcome by cold swaging the final product ten per cent. Reductions of 8X and 15X were used in this work.⁽¹¹⁾ The bonds produced by 15X reduction were reported to withstand growth from thermal cycling as high as 6 to 6-1/2 per cent with 200 cycles, 100 to 550 C. Cold swaging, beta treating, and various other tests failed to separate the 15X-reduced bond. The bond produced by an 8X reduction separated during thermal cycling.

A brief report by ORNL⁽¹²⁾ also gave promise of successful extrusion cladding of zirconium-uranium at 600 to 620 C.

Diffusion

Studies^(13, 14) of zirconium-uranium diffusion couples showed only slight diffusion after several days at 500 to 600 C. At higher temperatures, 700 to 800 C, extensive diffusion was observed in all cases with heat-treating times of 2, 6, and 12 days.⁽¹³⁾

Properties

Limited additions of zirconium increase the hardness of uranium.^(15, 16) Further additions may result in hardness plots similar to those in Figure 2.⁽³⁾

FIGURE 2. HARDNESS OF URANIUM-ZIRCONIUM ALLOYS⁽³⁾

A-2085

Creep data were obtained on zirconium-uranium alloys containing 17 to 90 atomic per cent zirconium using loads of 500 psi and at a temperature of 815 C. (17) Maximum creep resistance was obtained in alloys of 69.5 and 90 atomic per cent zirconium. These results and data from additional tests at 982 C are summarized in Table 1.

The properties of high-zirconium-uranium alloys have been studied rather intensively. Recent surveys of this work are available. (18, 19)

CHROMIUM-URANIUM ALLOYS

The Equilibrium Diagram

The general features of the chromium-uranium equilibrium diagram are well established, although precise data are not available on all portions of the system. The diagram shown in Figure 3 is based largely on the data of Daane and Wilson (20) although some refinement was taken from other sources of information.

Daane and Wilson (20) showed by combined methods, utilizing X-ray diffraction, thermal analysis, and metallographic examination, that no compounds occurred in the system. This has been confirmed by a study of diffusion samples at this laboratory. A eutectic occurs at about 20 atomic per cent chromium and 859 C. The solubility of uranium in chromium appears to be small. The lattice constant obtained from a furnace-cooled 19.9 per cent uranium alloy was $2.878 \pm 0.02\text{\AA}$. (20) This is the same as the lattice constant of pure chromium, within experimental error.

The solubility of chromium in gamma uranium is a maximum of four atomic per cent. This probably decreases to two or three per cent at the eutectoid temperature of 730 C. (20) The beta-uranium solubility is less than 2.5 atomic per cent chromium as reported by Daane. (20) A more accurate estimate is about one atomic per cent. (21) This was estimated from data obtained during a study of the transformational characteristics of alloys containing 0.6 and 1.8 atomic per cent chromium.

The beta-to-alpha eutectoid, Figure 3, occurs at 625 C. (22) The solubility in the alpha region is less than in the beta, but is unknown.

Recently, a report appeared in the literature (23) indicating that a high-temperature transition from body-centered cubic to face-centered cubic occurs in chromium just below the melting temperature. Since this transition is not well established and since it does not alter the chromium-

TABLE 1. SHORT-TIME CREEP DATA FOR HOT-ROLLED URANIUM-ZIRCONIUM ALLOYS⁽¹⁷⁾

Composition, Atomic Per Cent Zirconium	Test Temperature, C	Load, psi	Time, hours	Elongation, per cent*	Remarks
17	815	500	1 2	1 2	
28	815	500	-	7	Failed on loading
43	815	500	1 1-1/2 7	1 2 10	
69.5	815	500	57 78	1 2	
90	815	500	42 82	1 2	
27	982	250	--	6	Failed on loading
45	982	500	7	14	
69.5	982	500	3/4	15-1/2	
82	982	500	1/2 1 5-1/2	1 2 10	
87	982	500	< 1/2	16	Broke in < 1/2 hour at 16 per cent elongation

*Elongation is expressed as per cent elongation for a one-inch gage length. Specimens were 0.25 inch in diameter.

Alloys were prepared by arc melting.

FIGURE 3. URANIUM-CHROMIUM EQUILIBRIUM DIAGRAM

A-2086

uranium diagram in the region of working temperatures, this portion of the diagram is left open. The remainder of the diagram, as presented, is believed to be reliable and suitable for general use.

Properties

Survey of the literature turned up few data on properties of these alloys. Seybolt^(24,25) obtained hardness data for alloys in various heat-treated conditions. Little indication of age hardening was observed.

A general study of uranium-alloy mechanical properties is now under way at this laboratory. Preliminary data on a few chromium-uranium alloys are included in Table 2 along with some properties of pure uranium.⁽²⁶⁾

COLUMBIUM-URANIUM ALLOYS

Equilibrium Diagram

A partial diagram is shown in Figure 4 for columbium-uranium alloys. The liquidus-solidus curves were taken from the literature.⁽²⁷⁾ These data are tentative, but are in general agreement with rough observations from this laboratory. Metallographic examination of a series of alloys quenched from 1200 C, and varying from 39 to 100 atomic per cent columbium, revealed single-phase structures. Presumably, all were in the gamma region as shown in Figure 4. A series of alloys ranging up to 52 per cent was also in a single-phase region, as quenched from 1000 C. This is plotted in Figure 4 also.

The diagram in the beta and beta-plus-gamma region was studied thoroughly by the authors using a combination of metallographic examination and thermal analysis. The solubility in the beta range is a maximum of two atomic per cent at a eutectoid temperature of 660 C. The beta-plus-gamma region extends to about 14 or 15 atomic per cent columbium at the eutectoid temperature, Figure 4. The solubility of columbium in alpha uranium is less than one atomic per cent at 600 C, but is not known precisely.

Study of alloys up to 52 atomic per cent columbium were conducted after 500 C treatment by both X-ray and metallographic examination. Only alpha uranium and a high-columbium body-centered cubic phase were observed. It was found that equilibrium was approached rather rapidly in the beta and beta-plus-gamma range of temperatures and composition. At alpha temperatures, equilibrium is sluggish and is increasingly slow with increased

TABLE 2. SOME MECHANICAL PROPERTIES OF URANIUM
AND DILUTE CHROMIUM-URANIUM ALLOYS

Composition		Test Temperature, C	Yield Strength, 0.2% Offset, psi	Ultimate Strength, psi	Modulus of Elasticity, 10 ⁶ psi
Weight Per Cent	Atomic Per Cent				
Pure U	-	R. T.	26,000	88,400	22.7
Ditto	-	300	18,800	31,570	20.8
"	-	500	5,450	10,450	12.9
0.05 Cr	0.2	R. T.	-	126,000	20.9
Ditto	Ditto	100	37,000	104,500	-
"	"	300	32,000	44,500	14.8
"	"	500	10,500	13,050	-
0.12 Cr	0.6	300	36,400	54,900	18.1

Note: The pure uranium was alpha rolled and annealed at 600 C for 12 hours.
The alloys were alpha rolled and annealed at 550 C for one hour.

FIGURE 4. URANIUM-COLUMBIUM EQUILIBRIUM DATA

columbium content. For example, tentative observations showed that two or three weeks at 500 C were required to produce appreciable precipitation of alpha uranium in 39 and 52 atomic per cent alloys.

The diagram, Figure 4, is in incomplete form, since the exact nature of the center portion of the diagram is uncertain. However, the major features of the diagram are fairly certain. These are, first, complete solubility between the gamma uranium and columbium; secondly, the absence of compounds in the system. The high-uranium region is believed to be correct as shown and described.

Diffusion

Reports in the literature⁽¹³⁾ indicate that 144 hours at 500 and 600 C does not produce sufficient diffusion in a columbium-uranium diffusion couple to be identified. At 800 C, appreciable diffusion did occur. Slight diffusion was observed after 432 hours at 600 C⁽²⁸⁾ and 144 hours at 700 C. Work by Stacy⁽²⁹⁾ showed that extensive diffusion occurred at higher temperatures. For example, extensive diffusion was observed between columbium and uranium during treatment of 100 hours at 1080 C.

Properties

Additions of columbium produce considerable strengthening of uranium. This can be further improved by age hardening. Figures 5 and 6 illustrate the properties obtained from a 1.8 atomic per cent alloy, and a series of alloys containing approximately 4, 8, and 15 atomic percentages of columbium.⁽³⁰⁾

Compression tests were made on alloys of 15 and 23 atomic per cent columbium up to 1050 C at rates of 0.1 inch per minute.⁽³⁰⁾ At room temperature, stresses of 200,000 psi or more were obtained. This dropped off rapidly to 6000 psi at 600 to 700 C for the 15 per cent alloy. In the range of 700 to 1000 C, stresses of about 5000 psi were obtained. In the 23 per cent alloy, the drop-off with increased temperature was gradual, and a stress of 10,000 psi was obtained at 1000 C. The slow drop-off of stress in this alloy is attributed to sluggish equilibrium.

Brief studies of creep properties of low-columbium-uranium alloys in vacuum have been made.⁽¹⁷⁾ A hot-rolled alloy containing three atomic per cent columbium supported a stress of 500 psi at 815 C with one per cent elongation in seven hours and two per cent elongation in 20 hours. A test

Note: Alloys were prepared by vacuum melting in magnesia using master alloys. Master alloys were produced by bomb reduction

FIGURE 5. TENSILE PROPERTIES OF URANIUM-COLUMBIUM ALLOYS AFTER GAMMA TREATING TWO HOURS AT 850 C. STARTING MATERIAL WAS HOT-ROLLED BAR ⁽³⁰⁾

A-2088

FIGURE 6. STRESS-STRAIN CURVES, URANIUM-COLUMBIUM IN TENSION⁽³⁰⁾

made with an as-cast one atomic per cent alloy produced one per cent elongation in "zero" hours and two per cent elongation in three hours under similar conditions.

VANADIUM-URANIUM ALLOYS

The Equilibrium Diagram

The diagram for these alloys was worked out⁽³¹⁾ on material prepared from iodide vanadium and good biscuit uranium. The study was made using combined thermal analysis and metallographic methods with some preliminary X-ray diffraction phase identification. No compounds occur in the system, Figure 7. A eutectic reaction occurs at about 18 atomic per cent vanadium and 1040 C. The solubility of vanadium is a maximum of 12 atomic per cent at the eutectic and decreases to nine per cent at 727 C where gamma transforms by a eutectoid reaction. The solubility in the beta range is two atomic per cent. Vanadium lowers the beta-to-alpha temperature to 652 C where a second-eutectoid isothermal was found. Little solubility of vanadium exists in the alpha range. For example, less than 1.5 atomic per cent is soluble at 600 C.

The solubility of uranium in vanadium is about four atomic per cent near the eutectic (1000 C) and decreases with decreasing temperature.

The general nature of some of these alloys is illustrated by the micrographs in Figures 8 through 13. Figure 8 shows an as-cast uranium structure. Addition of 15 atomic per cent vanadium, Figure 9, produced a rather complex structure. The alloy first formed as primary uranium surrounded by eutectic. Subsequent eutectoid reactions produced modification of both regions. A modified eutectic structure with primary dendrites in a 20 atomic per cent vanadium alloy is shown in Figure 10. Two-phase structures containing 47 and 80 atomic per cent vanadium are shown in Figures 11 and 12. High-uranium material surrounds the vanadium in both these alloys. A micrograph of pure vanadium is shown in Figure 13.

Properties

Hardness data in the as-cast condition were obtained at this laboratory for a number of alloys at both ends of the system. These are shown in Figure 14. The data are connected by a hypothetical line giving an approximate idea of the hardness of the complete alloy series in the as-cast condition.

FIGURE 7. URANIUM-VANADIUM CONSTITUTIONAL DIAGRAM

A-2090

FIGURE 8. PURE URANIUM, AS CAST

FIGURE 9. FIFTEEN ATOMIC PER CENT
VANADIUM ALLOY, AS CAST

FIGURE 10. TWENTY ATOMIC PER CENT
VANADIUM ALLOY, AS CAST

FIGURE 11. FORTY-SEVEN ATOMIC PER CENT
VANADIUM, AS CAST

250X

65402

FIGURE 12. EIGHTY ATOMIC PER CENT
VANADIUM, AS CAST

250X

66357

FIGURE 13. PURE VANADIUM

FIGURE 14. HARDNESS OF VANADIUM- URANIUM ALLOYS, AS CAST

MOLYBDENUM-URANIUM ALLOYS

The Equilibrium Diagram

The uranium-molybdenum alloy system has been studied by a number of investigators. Early work⁽³²⁾ showed that gamma uranium was stabilized by additions of about 23 to 28 atomic per cent molybdenum. Experiments indicated that the gamma in these alloys was retained even after long periods of annealing at 400 to 600 C. Somewhat similar results were also reported in the unclassified literature.⁽³³⁾ More recently, a tetragonal product of decomposition was reported⁽³⁴⁾ and was confirmed by work at Battelle.^(35, 36) This information was incorporated into the equilibrium diagram, as shown in Figure 15.

Data for the liquidus-solidus were taken from the literature,⁽³²⁾ and are in agreement with brief observations made at this laboratory. A peritectic reaction occurs at 1285 C. The solubility in the gamma uranium is 42 atomic per cent molybdenum at the peritectic, and decreases to 30 per cent at 600 C. The gamma can be transformed to a tetragonal product at temperatures below 575 to 600 C. This transformation is very sluggish in the range of 20 to 30 per cent. The rate of transformation decreases with increasing molybdenum composition, so that cold work and four weeks' annealing were required to produce appreciable transformation in a sample of 28 to 30 per cent molybdenum alloy.^(35, 36)

X-ray diffraction analyses of the tetragonal phase were made by spectrometer and by powder methods. The pattern obtained⁽³⁵⁾ differs from the earlier report⁽³⁴⁾ by the presence of diffraction maxima at 4.85A, 3.25A, and 2.17A. The unit cell previously reported⁽³⁴⁾ was body-centered tetragonal with $c_0=3.278\text{A}$ and $a_0=3.420\text{A}$. The additional diffraction maxima can be indexed on the tetragonal net by doubling the above unit-cell dimensions. The maxima listed above then correspond to the (110), (002), and (130) planes, Table 3. This may indicate the presence of an ordered structure; however, the analysis does not permit positioning of the atoms within the unit cell.

The solubility of molybdenum in beta uranium is a maximum of 1.0 per cent at the eutectoid temperature.⁽³⁵⁾ This was determined by a study in which differential thermal analysis and metallographic examination were correlated. The alpha-uranium solubility is about 0.5 atomic per cent molybdenum at 600 C.

The solubility of uranium in molybdenum is 1.8 per cent at 1200 C,⁽³⁶⁾ Figure 15.

FIGURE 15. URANIUM-MOLYBDENUM EQUILIBRIUM DIAGRAM

TABLE 3. X-RAY DIFFRACTION PATTERNS OF EPSILON PHASE

Body-Centered Tetragonal Phase: $a_0=3.420$, $c_0=3.278$, Reported by KAPL-212, CuK			Body-Centered Tetragonal Phase: $a_0=6.84$, $c_0=6.55$, Observed at BMI, FeK		
(hkl)	Relative Intensity	d	(hkl)	Relative Intensity	d
110	S	2.440	110	F	4.85
101	VS	2.390	002	VF	3.25
200	S	1.717	220	MS	2.44
002	M	1.646	202	S	2.39
211	VS	1.390	130	F	2.17
112	M	1.347	400	M	1.72
220	MW	1.213	004	MF	1.65
202	MW	1.184	422	S	1.39
310	S and	1.08	224	M	1.35
301	broad				
103	MW	1.041	440	MF	1.21
222	M	0.973	404	M	1.18
321	M	0.911	620	S	1.08
			602		
312	M	0.903	206	MW	1.04
123	M	0.889	444	M	0.97
400	MW	0.854			
004	VW	0.819			
411	S and	0.804			
330	broad				
303	MS	0.790			

Microstructures of a number of molybdenum-uranium alloys are shown in Figures 16, 17, 18, and 19. These are included to give an indication of the nature and variety of structures that occur in this system of alloys.

Properties

Hardness data from a number of cast molybdenum-uranium alloys were obtained at this laboratory. These are plotted in Figure 20 giving a rough idea of the hardness traverse that might be expected at a uranium-molybdenum alloy bond. The traverse is not complete in the high-uranium

250X

60229

FIGURE 16. TRANSFORMED STRUCTURE, FIVE ATOMIC PER CENT MOLYBDENUM-URANIUM, ROLLED, HOMOGENIZED AND QUENCHED FROM 1000 C

-31-

250X

73793

FIGURE 17. CORED GAMMA STRUCTURE, 27 ATOMIC PER CENT MOLYBDENUM-URANIUM, AS CAST

250X

78837

FIGURE 18. TWO PHASE STRUCTURE, 70 ATOMIC PER CENT MOLYBDENUM-URANIUM, AS CAST

250X

78845

FIGURE 19. PURE MOLYBDENUM, AS CAST

FIGURE 20. HARDNESS OF CAST MOLYBDENUM-URANIUM ALLOYS

A - 2222

alloys. Since these alloys possess transformed structures, some inflection may occur in this region. The general nature of the alloys in the as-cast condition is indicated by the labeled regions in the hardness plot.

The mechanical properties of molybdenum-uranium alloys up to eleven per cent molybdenum have been studied, ⁽³⁷⁾ and the alloys were found to be age hardenable. Results of compressive and tensile tests on alloys of 5 to 11 atomic per cent (2 to 5 weight per cent) molybdenum are included in Tables 4 and 5. A graphic comparison of the compressive stress-strain curves for a 4.9 atomic per cent molybdenum (2 weight per cent) alloy and extruded uranium are shown in Figure 21. ⁽³⁷⁾

Creep data have been obtained on molybdenum-uranium alloys containing 11 to 59 atomic per cent molybdenum. ⁽¹⁷⁾ These data are summarized in Table 6 and seem to indicate increasing creep resistance with increased molybdenum additions.

Diffusion

Various laboratories have undertaken studies of the diffusion of molybdenum-uranium samples. Little reliable data were obtained for the most part, however, diffusion was detectable after six days at 600 C and above. ⁽¹³⁾ A graph showing the thickness of the diffusion layer of a molybdenum uranium sandwich after six days at various temperatures is shown in Figure 22. Shear strengths of 10,000 psi or better have been obtained in similarly bonded specimens. ⁽³⁸⁾

84
TABLE 4. COMPRESSION TESTS ON FIVE ATOMIC PER CENT MOLYBDENUM ALLOYS⁽³⁷⁾

Composition		Heat Treatment	Yield Strength, psi		Modulus of Elasticity, 10 ⁶ psi
Atomic Per Cent	Weight Per Cent		0.2% Offset	0.02% Offset	
4.9	2.02	Quenched 700 C	78,500	35,000	17.7
4.9	2.02	Quenched 700 C, aged 2 hr 400 C	248,000	190,000	24.2
4.9	2.02	Quenched 700 C	93,000	45,000	16.7
4.8	2.00	Quenched 700 C, aged 2 hr 400 C	226,000	180,000	22.8
4.8	2.00	Quenched 700 C	103,000	60,000	14.8

TABLE 5. TENSILE-TEST RESULTS ON SOME CAST URANIUM-MOLYBDENUM ALLOYS⁽³⁷⁾

Composition		Heat Treatment	Yield Strength, 0.2% Offset, psi	Ultimate Strength, psi	Elongation Per Cent, 2 inches	Reduction in Area, per cent	Modulus of Elasticity, 10 ⁶ psi
Atomic Per Cent	Weight Per Cent						
4.8	2	700 C, quench	148,000	165,750	0.25	0	24
11.5	5	Ditto	-	93,750	3.0	4.4	-
11.5	5	"	-	89,850	9.4	11.1	-
7.1	3	700 C, quench aged 2 hr 300 C	135,000	175,700	7.5	-	18.6
7.1	3	Ditto	131,700	160,000	3.0	-	21
7.1	3	"	134,000	156,000	1.0	-	18.3

FIGURE 21. COMPRESSION STRESS-STRAIN CURVES, URANIUM-4.8 ATOMIC PER CENT MOLYBDENUM ALLOY⁽³⁷⁾

TABLE 6. SHORT-TIME CREEP DATA FOR URANIUM-MOLYBDENUM ALLOYS(17)

Composition, Atomic Per Cent Molybdenum	Test Temperature, C	Load, psi	Time, hours	Elongation, per cent*	Remarks
11	815	500	< 1 3	1 5	Hot rolled
16.5	815	500	7.5 18	1 2	Hot rolled
17	815	500	2.5 10	1 2	Hot rolled
27	815	500	45 160	1 1.85	As cast
59	815	500 1000 1500 2000 2500 5000	290** 433** 785** 910** 958** 1010**	0.56 0.8 1.8 2.05 2.14 2.32	As cast, nominal composition

* Elongation is expressed as per cent elongation of a one-inch gage length. Specimens were 0.25 inch in diameter.

** Continuous test, times are total times for each temperature and preceding temperatures.

FIGURE 22. TOTAL MAXIMUM DIFFUSION LAYER THICKNESS FORMED AFTER SIX DAYS FOR URANIUM WITH MOLYBDENUM

A-2223

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