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THE CONSTITUTION DIAGRAM OF
URANIUM-RICH URANIUM -
MOLYBDENUM ALLOYS

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June 1, 1951

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2

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URANIUM-MOLYBDENUM ALLOYS

Contract No. W-7405-eng-92

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TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	4
INTRODUCTION	5
EXPERIMENTAL PROCEDURE	6
Materials and Melting	6
Fabrication	8
Thermal Analyses	9
Heat Treatment and Metallography	11
X-Ray Examination	12
RESULTS	13
The Constitution Diagram	13
Epsilon-Phase Structure	27
BIBLIOGRAPHY	30
ACKNOWLEDGMENT	30
APPENDIX I	31

ABSTRACT

The molybdenum-uranium equilibrium diagram has been studied, and the results are presented up to 50 atomic per cent molybdenum.

Additions of molybdenum raise the melting point of uranium, forming a peritectic at about 1285 C. The solubility of molybdenum in gamma uranium is extensive. It decreases from 42 atomic per cent at the peritectic temperature to 30 per cent at lower temperatures. Alloys of about 28 to 30 per cent molybdenum content have been found to contain a metastable gamma. It can be transformed by cold work and prolonged annealing at temperatures below 575 to 600 C. X-ray diffraction studies of the transition product in epsilon phase indicate that it has a tetragonal structure.

The beta-uranium region is lowered by molybdenum additions to produce a eutectoid transformation at 658 ± 5 C. The maximum beta solubility is about 1.0 atomic per cent molybdenum. The alpha-uranium solubility is less than in the beta region, or about 0.5 per cent molybdenum at 600 C.

INTRODUCTION

Uranium-molybdenum alloys have been of interest for some time. The work of numerous cooperating laboratories was summarized in 1945⁽¹⁾ and a constitution diagram was published. The diagram proposed at that time was admittedly incomplete, and phase boundaries were drawn in arbitrarily in some cases. This diagram indicated that gamma uranium was stabilized to room temperature by addition of 24 to 28 atomic per cent molybdenum. A recent publication⁽²⁾ shows a generally similar diagram. However, the two diagrams differ in the nature of the alpha solubility and beta-to-alpha transition at low-molybdenum compositions.

Because of the tendency of molybdenum to stabilize the isotropic gamma-uranium phase, these alloys became of interest as a possible high-temperature fuel-element material. Consequently, a re-examination of the binary diagram was made to clear up uncertainties in the system. The findings from 0 to 50 atomic per cent molybdenum are presented in this report.

It was not within the scope of this investigation to redetermine the crystallographic structures of alpha-, beta-, and gamma-uranium phases. However, recent work has been done on both the alpha and beta phases^(3,4), using electrolytically deposited single crystals of uranium and uranium alloys. The analysis of the beta-uranium phase, it is reported, should require only a refinement of parameters⁽³⁾. The beta structure is reported to be tetragonal with a unit cell of 30 atoms. The unit-cell dimensions are $a_0 = b_0 = 10.52 \text{ \AA}$, and $c_0 = 5.57 \text{ \AA}$.

Recent studies of the alpha uranium⁽⁴⁾ revealed nothing inconsistent with the work of Jacob and Warren⁽⁵⁾, although some minor revision of the c_0 crystal parameter may be possible. The Jacob and Warren unit cell is orthorhombic with $a_0 = 2.852$ A, $b_0 = 5.865$ A, and $c_0 = 4.945$ A.

The gamma-uranium lattice was determined to be BCC with $a_0 = 3.467 \pm 0.005$ A⁽¹⁾ at room temperature. A similar value is reported in the unclassified literature⁽⁶⁾. These values were determined by extrapolation, using data obtained on molybdenum-uranium alloys in which the gamma phase was retained at room temperature.

EXPERIMENTAL PROCEDURE

Materials and Melting

Mallinckrodt Chemical Company's biscuit uranium was used for this work. The principal contaminants were carbon, silicon, nickel, aluminum, and phosphorus, which were present in traces. Faint traces of numerous other elements were also present. Typical analysis of the biscuit is shown in Table 1.

The molybdenum was obtained from Fansteel Corporation. Molybdenum analysis is also included in Table 1.

The uranium biscuit was cut into pieces for charging into crucibles of $3/4$ to $1-1/4$ inches in diameter. Each piece was polished electrolytically to remove oxide and was macro-etched. Only the cleanest pieces were used for melting. (Polishing and macro-etching methods are described in the Heat Treatment and Metallography section of this report.)

TABLE 1. MATERIAL ANALYSES

Mallinckrodt Biscuit		Fansteel Molybdenum	
Uranium			
Element	ppm	Element	Per Cent
C	600	Mo	99.9
Fe	20	C	0.015 max.
Ni	50-100	Ni	0.02 max.
Al	10-100	O	0.10 max.
Mo	20		
Cr	20		
V	20		
Si	8-40		
P	50		

Alloys up to 25 atomic per cent molybdenum were induction melted. This was done in beryllia crucibles at a vacuum of 20 microns or less. The charges consisted of chunks of uranium and minus 100-mesh molybdenum powder. After melting, ingots were cleaned electrolytically and examined in both longitudinal and transverse directions. If segregated, ingots were inverted and remelted. This procedure was followed until a uniform alloy was obtained.

Alloys of 30 to 50 atomic per cent molybdenum were prepared by arc melting under argon atmosphere. A tungsten electrode and water-cooled copper crucible were used in this work.

Uranium for arc melting was prepared in the manner described above; however, it was necessary to use chunk molybdenum because the arc scatters powdered metal.

After melting, ingots were inverted and remelted. Three to five melting cycles were required to produce uniform ingots of 10 to 25 grams.

Ingots of 50 to 75 grams required a revised melting procedure. After melting twice, these ingots were chipped on a shaper. Chipping was done at slow speed to avoid oxidation. The chips were mixed, compacted, and remelted. This procedure produced fairly uniform ingots.

Fabrication

Ingots were forged and rolled to 1/2-inch rods to improve the uniformity and to break up cast structures. Alloys up to 2.5 atomic per cent molybdenum were alpha rolled at 550 to 600 C with 2 to 5 minutes between passes. Those from 5 to 50 per cent were gamma rolled in the range of 800 to 1100 C with 2 minutes between passes. The higher temperatures were required for the alloys of higher molybdenum content.

Alloys from 1 to 30 per cent molybdenum have been cold worked up to 75 per cent after hot rolling and gamma annealing.

Alloys of 1 to 3 per cent molybdenum cracked during quenching from either the beta- or gamma-phase regions. Furnace cooling or air cooling avoided this difficulty.

Thermal Analyses

Thermal analyses were made, using samples of 40 to 50 grams cut from half-inch-diameter rods. A differential thermocouple and neutral sample arrangement⁽⁷⁾ was used to detect transformations while heating and cooling at uniform rates. A diagram of this arrangement is shown in Figure 1. The neutral sample should be of some material with thermal properties similar to those of the alloys being tested and should not have a transformation in the range of temperatures of testing. Tantalum is a good material to use in this case.

Allotropic modifications were readily detected using a bare thermocouple bead, Figure 1. The end of the thermocouple hole was packed with refractory to prevent thermocouple-to-specimen contact. This arrangement gives rapid response because of the direct radiation from the specimens upon the bead.

Best results were obtained after one or more preliminary cycles through transformation temperatures. Heating data thus obtained generally were reliable. It was found that cooling data were generally in error, because allotropic transformations were supercooled. For example, a 2.5 per cent molybdenum sample supercooled 80 to 100 C while cooling at 2 C per minute.

Analyses were not made on alloys of more than 12 per cent molybdenum.

Note: Thermocouple wires protected with refractory spaghetti.
Bead is open to radiation from specimen hole.

FIGURE 1. DIFFERENTIAL THERMOCOUPLE FOR THERMAL ANALYSIS

Heat Treatment and Metallography

Samples for chemical analyses were cut from both ends and from the center of one-half-inch rolled rods. The method of sampling small arc-melted ingots depended upon their size and shape. Sometimes, whole metallographic samples of these small ingots were submitted for chemical analyses after thorough metallographic examination.

Before heat treating for metallographic examination, sections of the rolled alloys were homogenized by soaking for 100 hours at 1000 C, unless other treatment is indicated.

All heat treatments were made under a vacuum of five microns or less.

Specimens were cut using No. 237 Manhattan Rubber Division cutoff wheels under a water spray. These were ground wet through the usual rough papers and were finished wet on 240-, 400-, and 600-grit papers.

Alloys up to 50 atomic per cent molybdenum were polished electrolytically at 50 to 60 volts in a solution of chromic and acetic acids (1 part base solution 100 g CrO_3 and 118 cu cm H_2O ; 3 parts glacial acetic acid). In some cases, surface films formed rapidly during polishing. This was avoided by increasing the voltage and current density. The polishing time varied from 10 to 40 seconds.

Specimens occasionally polished and etched simultaneously. Otherwise, they were etched by lowering the voltage in the polishing solution.

Best results usually were obtained at 6 to 10 volts. These etches also served for macro examination.

Relief was sometimes troublesome in high-magnification examination of two-phase alloys. This was avoided by polishing mechanically on billiard cloth with "Tin(1c)" oxide and electroetching.

Etching times and characteristics varied with different structures. A grain-boundary etch was produced on retained gamma-phase alloys. Phase boundaries were outlined quickly in two-phase alloys. Alpha-phase material etched readily with partial grain-boundary outlines and preferential grain lustre. Retained beta-phase material was polished easily, but did not etch in this solution. The beta structure was best observed in the as-polished condition with polarized light.

X-Ray Examination

X-ray diffraction spectrometer analyses were made on metallic-graphic-specimen surfaces. A rotating jig was used to eliminate large grain effects where these occurred.

Filings were made and sealed in quartz capillary tubes. These were examined in a powder camera before and after heat treatment to determine the structure of the intermediate phase occurring at 30 atomic per cent molybdenum and to supplement other data.

The results of X-ray diffraction studies are discussed briefly in the results section of this report, and a summary of X-ray data is tabulated in Appendix I for reference. X-ray spectrometer data were

complicated by transformation in quenched samples containing up to five per cent molybdenum. As a result, few X-ray data are reported on alloys of these compositions.

RESULTS

The Constitution Diagram

The equilibrium diagram of molybdenum-uranium alloys up to 50 atomic per cent molybdenum is shown in Figure 2. Liquidus-solidus data are reproduced from previous work⁽¹⁾. These data are in agreement with checks made during the course of this investigation. The findings obtained on the remainder of the diagram are plotted in Figure 2. The legend explains how the plotted data were obtained. A summary of X-ray data is tabulated in Appendix I of this report.

Gamma uranium forms by a peritectic reaction from liquid and delta phases at about 1285 C and 42 atomic per cent molybdenum, as shown in Figure 2. The gamma-phase solubility decreases with decreased temperature to 28 to 30 per cent at 575 to 600 C. At these temperatures and compositions, the gamma transforms to an intermetallic phase, designated as epsilon (Figure 2).

The boundaries of the epsilon phase are drawn dotted to indicate that the work on this region is incomplete. The gamma-plus-epsilon-phase region is arbitrarily drawn in with dotted lines, in accordance with the phase rule.

Metallographic Data

- Two-phase
- △ One-phase

Metallographic and Xray Data

- Two-phase
- ▲ One-phase

FIGURE 2. U-Mo EQUILIBRIUM DIAGRAM

The transformation from gamma to epsilon at 28 to 30 per cent is extremely sluggish and occurs only after working and prolonged thermal treatment below the transition temperature. The sluggishness of the gamma phase decreases as the molybdenum content is decreased, and in alloys of 12 per cent molybdenum or less, the gamma transforms to alpha and epsilon phases during furnace cooling.

Figures 3 to 8 show a series of micrographs of samples with increasing molybdenum content. These samples were quenched from the gamma-phase region. The microstructures in Figures 3, 4, and 5 are rather complex, and it should be kept in mind that these are nonequilibrium structures formed during quenching. The 0.8 per cent sample, Figure 3, transformed to alpha during quenching. A high-temperature phase, probably beta, was retained in a two per cent molybdenum sample and transformed partially to alpha, forming a Widmanstätten pattern, Figure 4. Transformation of the retained phase to alpha phase continues during aging at room temperature. A Widmanstätten pattern also was obtained in a 5 per cent sample quenched from the gamma, Figure 5, but no high-temperature phase was detected by X-ray. This sample was probably a supersaturated alpha-like solution.

A tetragonal transition phase was retained in a 12 per cent sample, Figure 6. This was different from the tetragonal epsilon phase and disappeared readily during annealing at 450, 500, and 600 C. The retained-gamma microstructure, Figure 6, is evidence that the transition phase was formed at low temperatures where diffusion is slow. It is anisotropic when viewed under polarized light, Figure 6.

250X

72487

FIG. 3--0.8 PER CENT Mo-U, ROLLED, HOMOGENIZED, AND QUENCHED FROM 900 C

250X

65370

FIG. 4--2 PER CENT Mo-U, ROLLED, HOMOGENIZED, AND QUENCHED FROM 1000 C. AGED 30 DAYS AT ROOM TEMPERATURE

250X

60229

FIG. 5--5 PER CENT Mo-U, ROLLED, HOMOGENIZED, AND QUENCHED FROM 1000 C

POLARIZED 100X

65376

FIG. 6--12 PER CENT Mo-U, ROLLED, HOMOGENIZED, AND QUENCHED FROM 1000 C

The gamma phase is retained during quenching or during furnace cooling in a 20 per cent molybdenum alloy, Figure 7. A 27 per cent molybdenum, as-cast alloy is shown in Figure 8. This is a segregated structure containing gamma of varying compositions.

The beta-phase solubility increases as the temperature is decreased, Figure 9. The solubility at 700 C. is 0.8 per cent. This increases to 1.0 per cent molybdenum at 658 C. At this temperature, a eutectoid reaction occurs and beta transforms to alpha and gamma, Figure 9.

The beta-plus-gamma region extends to approximately 6 per cent molybdenum, Figure 9.

The beta and beta-plus-gamma regions were determined by thermal and metallographic data, Figure 9. Some micrographs are shown in Figures 10 to 18, which were obtained by quenching from the vicinity of the beta-plus-gamma region. All of these are in accord with the diagram in Figure 9.

Figures 10, 11, and 12 document the increased beta solubility with decreased temperature. They show decreasing amounts of a second phase as the temperature is lowered from 730 to 700 C in 0.8 per cent molybdenum samples. Beta-plus-gamma structures obtained by quenching 1.25 per cent samples from similar temperatures are illustrated in Figures 13, 14, and 15. A 5 per cent sample quenched from 730 C was in the gamma region, Figure 16.

It was usually impossible to retain all the equilibrium phases in these samples. However, it is believed that the physical appearance of equilibrium structures was retained and observed.

250X

74718

FIG. 7--20 PER CENT Mo-U, ROLLED,
HOMOGENIZED, AND QUENCHED FROM
1000 C

250X

73793

FIG. 8--27 PER CENT Mo-U, AS CAST

250X

65672

FIG. 10--0.8 PER CENT Mo-U, ROLLED
AND HOMOGENIZED. TREATED 2 HOURS AT
830 C, FURNACE COOLED TO 730 C, 20
HOURS AT 730 C, AND QUENCHED

250X

72499

FIG. 11--0.8 PER CENT Mo-U, ROLLED
AND HOMOGENIZED. TREATED 20 HOURS
AT 710 C, AND QUENCHED

FIGURE 9. SECTION OF U-Mo EQUILIBRIUM DIAGRAM

250X

72488

FIG. 12--0.8 PER CENT Mo-U, ROLLED AND HOMOGENIZED. TREATED 20 HOURS AT 700 C, AND QUENCHED

250X

72504

FIG. 13--1.25 PER CENT Mo-U, ROLLED AND HOMOGENIZED. TREATED 2 HOURS AT 830 C, FURNACE COOLED TO 730 C, 20 HOURS AT 730 C, AND QUENCHED

250X

72490

FIG. 14--1.25 PER CENT Mo-U, ROLLED AND HOMOGENIZED. TREATED 2 HOURS AT 830 C, FURNACE COOLED TO 710 C, 20 HOURS AT 710 C, AND QUENCHED

250X

72493

FIG. 15--1.25 PER CENT Mo-U, ROLLED AND HOMOGENIZED. TREATED 20 HOURS AT 700 C, AND QUENCHED

It was reasoned that, if these observed structures represented equilibrium structures in appearance, holding increasing time at temperature should cause a coalescence of the second phase. This is shown in Figures 17 and 18. These micrographs show samples of 1.25 per cent molybdenum alloys quenched after 1 and 20 hours at 700 C. It is clear that the second phase has coalesced with increased time.

Further proof that these micrographs represent true structures is the different grain-boundary outlines produced by heating and cooling into the beta-plus-gamma region. Figure 18 shows a beta grain outlined by gamma-phase particles and also a general precipitation of gamma particles within the grains. Figure 19 shows beta phase outlining former gamma grains. The gamma plates and particles within the grains are the remains of former gamma grains.

Returning to the equilibrium diagram, beta transforms in a eutectoid reaction at 658 C and forms alpha and gamma phases. This was established by both thermal and metallographic data. Note that the alpha-plus-beta region was located by thermal analysis of an 0.25 per cent sample, Figure 9.

The alpha solubility at 600 C is about 0.5 atomic per cent molybdenum, Figure 9. The solubility is believed to decrease slightly with temperature. However, this was not determined accurately, because of the difficulty in obtaining equilibrium at the lower temperatures. The alpha solubility was determined by cold working and heat treating low-molybdenum alloys to produce a second-phase precipitate. A typical

250X

65655

FIG. 16--5 PER CENT Mo-U, ROLLED AND HOMOGENIZED. TREATED 20 HOURS AT 730 C, AND QUENCHED

250X

72502

FIG. 17--1.25 PER CENT Mo-U, ROLLED AND HOMOGENIZED. TREATED 1 HOUR AT 700 C, AND QUENCHED

250X

72494

FIG. 18--1.25 PER CENT Mo-U, ROLLED AND HOMOGENIZED. TREATED 20 HOURS AT 700 C, AND QUENCHED

250X

72496

FIG. 19--1.25 PER CENT Mo-U, ROLLED AND HOMOGENIZED. TREATED 2 HOURS AT 830 C, FURNACE COOLED TO 700 C, 75 HOURS AT 700 C, AND QUENCHED

structure which was obtained in this manner is shown in Figure 22. This is a micrograph of a 0.8 per cent sample which was cold worked 40 per cent, heat treated 20 hours at 600 C, and quenched.

Samples of 2 and 5 per cent alloys were probably in the alpha-plus-gamma region when quenched from 655 C, Figures 20 and 21. The alpha-plus-gamma region is further documented by micrographs of alloys quenched from 640, 620, and 580 C. Micrographs of 2, 5, and 12 per cent alloys quenched from 640 C are shown in Figures 23, 24, and 25. The grain-boundary outlines were produced by cooling from the gamma to the heat-treating temperature. The 12 per cent alloy, Figure 25, was in the gamma region at 640 C.

Alloys of 2, 5, and 12 per cent molybdenum were quenched from 620 C. Grain-boundary outlines were produced in the 2 and 5 per cent alloys, Figures 26 and 27, by furnace cooling from the gamma to 620 C. Annealing at 620 C did not produce an alpha precipitate in the gamma phase of a 12 per cent sample. However, annealing at 600 C produced a precipitate which did not go back in solution when reannealed at 620 C, Figure 28.

Micrographs of samples treated at 580 C are shown in Figures 29, 30, and 31. These samples were heated directly to 580 C and quenched after 100 hours at temperature. The precipitate in Figure 29 follows a Widmanstätten pattern, resulting from prior homogenization and quenching. The 5 and 12 per cent samples, Figures 30 and 31, contain a lamellar structure which grew as nodules. These samples also contained a fine matrix precipitate which could be resolved at higher magnification.

250X

65653

FIG. 20--2 PER CENT Mo-U, ROLLED AND HOMOGENIZED. TREATED 2 HOURS AT 830 C, FURNACE COOLED TO 655 C, 20 HOURS AT 655 C, AND QUENCHED

250X

65364

FIG. 21--5 PER CENT Mo-U, ROLLED AND HOMOGENIZED. TREATED 2 HOURS AT 830 C, FURNACE COOLED TO 655 C, 20 HOURS AT 655 C, AND QUENCHED

250X

72500

FIG. 22--0.8 PER CENT Mo-U, ROLLED AND HOMOGENIZED. COLD WORKED 40 PER CENT, TREATED 20 HOURS AT 600 C, AND QUENCHED

250X

73796

FIG. 23--2 PER CENT Mo-U, ROLLED AND HOMOGENIZED. TREATED 2 HOURS AT 830 C, FURNACE COOLED TO 640 C, 20 HOURS AT 640 C, AND QUENCHED

250X

65651

FIG. 24--5 PER CENT Mo-U, ROLLED AND HOMOGENIZED. TREATED 2 HOURS AT 830 C, FURNACE COOLED TO 640 C, 20 HOURS AT 640 C, AND QUENCHED

250X

65652

FIG. 25--12 PER CENT Mo-U, ROLLED AND HOMOGENIZED. TREATED 2 HOURS AT 830 C, FURNACE COOLED TO 640 C, 20 HOURS AT 640 C, AND QUENCHED

250X

73797

FIG. 26--2 PER CENT Mo-U, ROLLED AND HOMOGENIZED. TREATED 2 HOURS AT 830 C, FURNACE COOLED TO 620 C, 20 HOURS AT 620 C, AND QUENCHED

250X

65363

FIG. 27--5 PER CENT Mo-U, ROLLED AND HOMOGENIZED. TREATED 2 HOURS AT 830 C, FURNACE COOLED TO 620 C, 20 HOURS AT 620 C, AND QUENCHED

250X

65378

FIG. 28--12 PER CENT Mo-U, ROLLED AND HOMOGENIZED. TREATED 40 HOURS AT 600 C, HEATED TO 620 C, 70 HOURS AT 620 C, AND QUENCHED

250X

65366

FIG. 29--2 PER CENT Mo-U, ROLLED AND HOMOGENIZED. TREATED 100 HOURS AT 580 C, AND QUENCHED

250X

65367

FIG. 30--5 PER CENT Mo-U, ROLLED AND HOMOGENIZED. TREATED 100 HOURS AT 580 C, AND QUENCHED

250X

65369

FIG. 31--12 PER CENT Mo-U, ROLLED AND HOMOGENIZED. TREATED 100 HOURS AT 580 C, AND QUENCHED

Micrographs showing the formation of alpha-plus-epsilon structures in 20 per cent molybdenum samples are shown in Figures 32, 33, and 34. These samples were cold worked 75 per cent and annealed at successively lower temperatures. Figure 32 shows a gamma structure obtained at 600 C. Figures 33 and 34 are alpha-plus-epsilon structures formed at 550 and 500 C. These data are consistent with the equilibrium diagram, Figure 2.

The principal data on the epsilon-phase and epsilon-plus-delta-phase regions, Figure 2, were obtained by X-ray. These data were tentatively verified by metallographic examination. A thorough metallographic study of the epsilon-phase region is in progress and will be reported at a later date.

Epsilon-Phase Structure

X-ray analyses of the intermetallic phase in the molybdenum-uranium system were made both by X-ray spectrometer and by powder methods. The pattern obtained for this phase differs from the previously reported analysis⁽⁸⁾ by the presence of diffraction maxima at 4.85 Å, 3.25 Å, and 2.17 Å. The unit cell previously reported was body-centered tetragonal with $c_0 = 3.278$ Å and $a_0 = 3.420$ Å. The additional diffraction maxima at 4.85 Å, 3.25 Å, and 2.17 Å can be indexed on the tetragonal net by doubling these unit-cell dimensions. The maxima listed above then correspond to the (110), (002), and (130) planes, respectively, of the doubled cell, Table 2.

This may indicate an ordered structure; however, the present state of analysis does not permit positioning of the atoms within the unit cell.

250X

74719

FIG. 32--20 PER CENT Mo-U, ROLLED AND HOMOGENIZED. COLD WORKED 75 PER CENT, TREATED 24 HOURS AT 600 C, AND QUENCHED

250X

74714

FIG. 33--20 PER CENT Mo-U, ROLLED AND HOMOGENIZED. COLD WORKED 75 PER CENT, TREATED 24 HOURS AT 550 C, AND QUENCHED

250X

74715

FIG. 34--20 PER CENT Mo-U, ROLLED AND HOMOGENIZED. COLD WORKED 75 PER CENT, TREATED 24 HOURS AT 500 C, AND QUENCHED

TABLE 2. X-RAY DIFFRACTION PATTERNS OF EPSILON PHASE

Body-Centered Tetragonal Phases $a_0 = 3.420$, $c_0 = 3.278$, Reported by KAPL-212, CuK α			Body-Centered Tetragonal Phases $a_0 = 6.84$, $c_0 = 6.55$, Observed at BNL, FeK α		
(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 } 301 }	S and broad	1.08	224	M	1.35
103	MW	1.041	440	MF	1.21
222	M	0.973	404	M	1.18
321	M	0.911	620 } 602 }	S	1.08
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 } 330 }	S and broad	0.804			
303	MS	0.790			

BIBLIOGRAPHY

1. Ahmann, Donald, Snow, A. I., and Wilson, A. S., "The Uranium-Molybdenum Binary System", CT-2946, July, 1945 (SECRET).
2. Pfeil, P. C. L., "The Constitution of Uranium-Molybdenum Alloys", J. Inst. Metals, Vol. 77, pp. 553-70.
3. Tucker, C. W., Jr., "An Approximate Crystal Structure of the Beta Phase of Uranium", KAPL-338, July 7, 1950 (SECRET).
4. Knolls Atomic Power Laboratory, Monthly Report for October, 1948, Metallurgy Section, Memo J.P.H.-30 (SECRET).
5. Jacob, C. W., and Warren, B. E., J. Am Chem. Soc., Vol. 59, pp. 2588-91, 1937.
6. Wilson, A. S., and Rundle, R. E., "The Structures of Uranium Metal", Acta Crystallographica, Vol. 2, p. 126, 1949.
7. Natl. Bur. Standards, Tech. Paper 170, 1921.
8. Knolls Atomic Power Laboratory, Monthly Report for June, 1948, Metallurgy Division, KAPL-212 (SECRET).

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APPENDIX I

SUMMARY OF PHASE IDENTIFICATION BY X-RAY DIFFRACTION

No.	Atomic Per Cent Mo	Quench Temp, C	Phases	Remarks
1	0.8	1000	αU	
2	1.25	1000	$\beta U + \alpha U$	Partially transformed to α ; continues transforming at room temperature
3	2	1000	βU	Ditto
4	5	1000	?	Probably supersaturated alpha- like solution
5	12	1000	X	Transition phase, tetragonal
6	20	1000	βU	----
7	27	1000	βU	----
8	40	1000	$\beta U + \delta$	
9	2	800	βU	See 3 above
10	5	800	?	See 4 above
11	12	800	X	See 5 above
12	20	800	βU	----
13	27	800	βU	----
14	40	800	$\beta U + \delta$	----
15	12	600	$\alpha U + \beta U$	----
16	20	600	βU	----
17	27	600	βU	----
18	40	600	$\epsilon + \delta$	----
19	2	580	$\alpha U + \beta U$	----
20	5	580	$\alpha U + \beta U$	----
21	9	580	$\alpha U + \beta U$	----
22	12	580	$\alpha U + \beta U$	----
23	20	550	$\alpha U + \epsilon$	----
24	27	550	$\alpha U + \epsilon$	----
25	40	550	$\epsilon + \delta$	----
26	12	500	$\alpha U + \epsilon$	----
27	12	450	$\alpha U + \epsilon$	----
28	20	450	$\alpha U + \epsilon$	----
29	27	450	$\alpha U + \epsilon$	----
30	40	450	$\epsilon + \delta$	----