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URANIUM ALLOYS FOR HIGH-TEMPERATURE
APPLICATION

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June 25, 1956

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URANIUM ALLOYS FOR HIGH-TEMPERATURE APPLICATION

Henry A. Saller, Ronald F. Dickerson,
and William E. Murr

Uranium-molybdenum and uranium-zirconium alloys are of interest as power-reactor fuels. This report deals with some physical properties of uranium-3.5, 5, 7, 9, and 12 w/o molybdenum and uranium-3, 5, 7, 10, 15, and 20 w/o zirconium alloys. Results of a heat-treatment study, hot-hardness and dilation data, and the effects of beta and gamma thermal cycling upon cylinders of both alloy groups are given.

In general, the addition of either zirconium or molybdenum to uranium improved elevated-temperature properties. Uranium-molybdenum alloys possessed greater strengths at elevated temperatures than uranium-zirconium alloys.

Dilation information was obtained upon both uranium-molybdenum and uranium-zirconium alloys in two conditions of heat treatment. A slight decrease in length of uranium-zirconium specimens occurred during dilation studies when cooled from 950 C. Conversely, an increase in length occurred with uranium-molybdenum specimens where a transformation was detected.

Thermal cycling revealed that uranium-molybdenum alloys had a greater degree of thermal stability when cycled above 680 C than did the uranium-zirconium alloys. Uranium-zirconium alloys were thermally stable only if cycled below the transformation temperature.

INTRODUCTION

The proposed use of uranium-zirconium and uranium-molybdenum alloys as power-reactor fuels requires that information be obtained concerning the mechanical and metallurgical properties of the alloys. An investigation was undertaken to provide information on uranium-3.5, 5, 7, 9, and 12 w/o molybdenum and 3, 5, 7, 10, 15, and 20 w/o zirconium alloys.

This report is the first of two to be written on the properties of uranium-molybdenum and uranium-zirconium alloys, and gives results of the studies to date. Included are a heat-treatment study, hot-hardness and linear-thermal-expansion data, and behavior of specimens of the alloys in thermal cycling.

The second report will consist of mechanical-property studies of the same groups of alloys at elevated temperatures, and will be issued at a later date.

PREPARATION OF ALLOYS

All alloys were prepared by combined induction and consumable-electrode arc-melting processes. The alloys were first induction melted in vacuum and poured from ZrO_2 crucibles at a temperature of 1590 C into cold graphite molds. This produced ingots 1-1/2 in. in diameter and approximately 8 in. long. The ingots were then melted by the consumable-electrode arc-melting process. All melts were produced from center-cut biscuit and high-purity molybdenum or crystal-bar zirconium. After melting, the 2-1/2-in. consumable ingots were turned to a smooth surface for forging. Chips obtained from turning the ingots were analyzed for zirconium or molybdenum content. Table 1 lists chemical analyses for both groups of alloys.

After melting, the ingots were reduced by forging, rolling, and swaging to rod approximately 7/8 in. in diameter. The rod was sectioned and additional rolling was carried out on a portion of each alloy to produce 1/2-in. -diameter material for heat-treatment studies. Table 2 lists forging and rolling data for both the uranium-molybdenum and uranium-zirconium alloys.

All of the alloys were fabricated without difficulty.

Following the rolling, the molybdenum alloys were cold swaged to approximately 40 per cent reduction in area. They were then annealed in a salt bath for 1 hr at 1100 F to prevent cracking.

The zirconium alloys were annealed for 1 hr in vacuum. Following the anneal they were reduced 30 to 35 per cent by cold rolling and then re-annealed to prevent cracking.

HEAT TREATMENT

Uranium-Zirconium Alloys

The objectives of heat treating uranium-zirconium alloys were threefold:

TABLE 1. CHEMICAL ANALYSIS OF URANIUM-ZIRCONIUM
AND URANIUM-MOLYBDENUM ALLOYS

Composition (Balance Uranium), w/o	
Nominal	Chemical Analysis
3.5 molybdenum	3.34 molybdenum
5.0 molybdenum	4.99 molybdenum
7.0 molybdenum	7.18 molybdenum
9.0 molybdenum	9.36 molybdenum
12.0 molybdenum	12.10 molybdenum
3.0 zirconium	2.95 zirconium
5.0 zirconium	4.96 zirconium
7.0 zirconium	7.07 zirconium
10.0 zirconium	9.86 zirconium
15.0 zirconium	15.5 zirconium
20.0 zirconium	20.0 zirconium

TABLE 2. FABRICATION HISTORY OF ALLOYS

Nominal Composition (Balance Uranium), w/o	Forging Temperature, F	Rolling Temperature, F
3.5 molybdenum	1125	1125
5.0 molybdenum	1500	1500
7.0 molybdenum	1600	1600
9.0 molybdenum	1800	1650
12.0 molybdenum	1800	1800
3.0 zirconium	1125	1125
5, 7, 10, 15 zirconium	1500	1500
20 zirconium	1650	1500

- (1) To produce a fine grain size in the alloys
- (2) To produce a variation in size and distribution of the alpha-uranium and epsilon phases
- (3) To produce a homogeneous structure as a means of eliminating or reducing preferential growth during irradiation.

The heat-treatment response of the uranium-zirconium alloys was determined on specimens approximately 1/2 in. in diameter and 1/4 in. thick. All specimens were heated in vacuum for 1 hr at 800 C before cooling. The structures obtained were a result of the cooling rates utilized. The heat treatments are listed below, along with a brief description of the objective for each specific treatment:

- A. Heat Treatment A consisted of heating specimens for 1 hr at 800 C and furnace cooling them. This is a standard treatment for uranium-zirconium alloys. Representative microstructures for this treatment are those of uranium-5 and 15 w/o zirconium alloys (Figure 1). The grain size showed a gradual decrease with zirconium content and a gradual change from the acicular structure of uranium-5 w/o zirconium to the lamellar structure of the uranium-15 w/o zirconium alloys.
- B. Heat Treatment B consisted of heating specimens for 1 hr at 800 C and furnace cooling them at the rate of 1/2 C per min between 750 and 570 C. This treatment was intended to provide equilibrium precipitates of gamma and epsilon uranium, and to coarsen the structure. Representative microstructures of this treatment are shown in Figure 2 for uranium-5 w/o and 15 w/o zirconium. The same trends appearing for Heat Treatment A appear in this group of photographs. However, the larger grain sizes and coarser structures are the apparent result of the slower controlled furnace cool.
- C. Heat Treatment C consisted of heating specimens for 1 hr at 800 C, then isothermally transforming them for 2 hr at 550 C and water quenching. This treatment was designed to provide numerous nucleation sites in the material. It was given to specimens as a single treatment and in combination with Heat Treatment D (Heat Treatments CD and CDD).

100X Polarized Light N27712

250X Bright Field N27713

Uranium-5 w/o Zirconium

100X Polarized Light N27714

250X Bright Field N27715

Uranium-15 w/o Zirconium

FIGURE 1. ALLOYS HEATED 1 HR AT 800 C AND FURNACE COOLED
(HEAT TREATMENT A)

100X Polarized Light N27716

250X Bright Field N27717

Uranium-5 w/o Zirconium

100X Polarized Light N27718

250X Bright Field N27719

Uranium-15 w/o Zirconium

FIGURE 2. SPECIMENS HEAT TREATED 1 HR AT 800 C, FURNACE COOLED TO 750 C, AND COOLED FROM 750 C TO 570 C AT A RATE OF 1/2 C PER MIN (HEAT TREATMENT B)

- D. Heat Treatment D consisted of heating specimens for 1 hr at 800 C, 5 min at 780 C, and isothermally transforming them for 2 hr at 550 C. The treatment was designed to increase randomization of structure. Examination revealed that Heat Treatments C, CD, and CDD produced essentially the same results. Heat Treatment D was repeated on specimens with the aim of increasing randomization. A sharp break in grain size resulting from the treatment occurred between specimens of uranium-7 w/o and 10 w/o zirconium. Typical structures produced by these treatments are those of uranium-5 and 10 w/o zirconium (Figure 3).
- E. Heat Treatment E consisted of heating specimens for 1 hr at 800 C, furnace cooling to 670 C, annealing at that temperature for 24 hr, and then furnace cooling to room temperature. Typical structures produced by this treatment are those of uranium-5 and 15 w/o zirconium alloys (Figure 4). The prolonged annealing time at 670 C has evidently succeeded in coarsening the phase particles present. Grain size again shows a gradual decreasing tendency with increased zirconium content.
- F. Heat Treatment F consisted of water quenching specimens after 1 hr at 800 C, reheating them to 670 C for 24 hr and then furnace cooling them. This treatment was designed to show structural variation obtained by holding gamma-quenched specimens at alpha plus gamma temperatures. It produced in alloys containing up to 10 w/o zirconium a martensitic structure that retained its features after being annealed at 670 C. Typical structures of Heat Treatment F are those of the 5 and 20 w/o zirconium alloys represented by photomicrographs in Figure 5.

In general, when uranium-zirconium alloys are cooled at slow rates there is a gradual change both in grain size and phase distribution with increasing zirconium content. Both grain size and particle size show a tendency toward refinement. However, upon rapid cooling from the gamma phase, there is apparently a fairly sharp division between 7 to 10 w/o zirconium with respect to grain sizes developed. The phase distribution also changes, but at a more gradual rate.

100X Polarized Light N27720

250X Bright Field N27721

Uranium-5 w/o Zirconium

100X Polarized Light N27722

250X Bright Field N27723

Uranium-10 w/o Zirconium

FIGURE 3. ALLOYS HEAT TREATED 1 HR AT 800 C, 2 HR AT 550 C, 5 MIN AT 780 C, 2 HR AT 550 C, 5 MIN AT 780 C, 2 HR AT 550 C, AND FURNACE COOLED (HEAT TREATMENT CDD)

100X Polarized Light N27724

250X Bright Field N27725

Uranium-5 w/o Zirconium

100X Polarized Light N27726

250X Bright Field N27727

Uranium-15 w/o Zirconium

FIGURE 4. SPECIMENS HEAT TREATED 1 HR AT 800 C, FURNACE COOLED TO 670 C, HELD 24 HR, AND FURNACE COOLED (HEAT TREATMENT E)

100X Polarized Light N27728

250X Bright Field N27729

Uranium-5 w/o Zirconium

100X Polarized Light N27730

250X Bright Field N27731

Uranium-20 w/o Zirconium

FIGURE 5. SPECIMENS HEAT TREATED 1 HR AT 800 C, WATER QUENCHED; 24 HR AT 670 C, AND FURNACE COOLED (HEAT TREATMENT F)

Uranium-Molybdenum Alloys

Each of the uranium-molybdenum alloys received two heat treatments. The purpose of these treatments was to produce specimens with retained-gamma structures and with nearly-transformed-gamma structures. Retained-gamma structures were produced by water quenching specimens from 800 C, and transformed structures were obtained by permitting transformation to take place at 500 C. Transformation time was a function of molybdenum content, with higher molybdenum alloys requiring a greater period of time for transformation. The heat treatments are listed below:

- G. 1 hr at 800 C, water quenched
- H. 1 hr at 800 C, air cooled (specimen protected in an evacuated glass envelope)
- J. 1 hr at 800 C, furnace cooled to 500 C, held 24 hr, furnace cooled
- K. 1 hr at 800 C, furnace cooled to 500 C, held 100 hr, furnace cooled
- L. 1 hr at 800 C, furnace cooled to 500 C, held 200 hr, furnace cooled
- M. 1 hr at 800 C, furnace cooled to 500 C, held 2 weeks, furnace cooled.

Figure 6a is of gamma-quenched uranium-5 w/o molybdenum given Heat Treatment G. The photomicrographs reveal the martensitic structure known as alpha prime, which is characteristic of the alloys with lower molybdenum contents. Figure 6b is of uranium-5 w/o molybdenum that was partially transformed by soaking at 500 C for 24 hr (Heat Treatment J). Transformation has resulted in the appearance of a precipitate of the alpha-uranium and the intermediate-delta phases.

Figures 7a and 7b are of uranium-12 w/o molybdenum alloys gamma quenched and transformed, respectively. The martensitic or alpha-prime structure present in the alloys of lower molybdenum contents is missing in the gamma-quenched specimen. However, in the transformed specimen, a precipitate borders the grain boundaries and is identified as alpha uranium and delta.

100X Polarized Light N27732

250X Bright Field N27733

a. Gamma-Quenched Uranium-5 w/o Molybdenum Heat Treated for 1 Hr at 800 C and Water Quenched (Heat Treatment G)

100X Bright Field N27734

250 X Bright Field N29518

b. Transformed Uranium-5 w/o Molybdenum Heat Treated for 1 Hr at 800 C, Furnace Cooled to 500 C, Held 24 Hr, and Furnace Cooled (Heat Treatment J)

FIGURE 6. GAMMA-QUENCHED AND TRANSFORMED URANIUM-5 w/o MOLYBDENUM SPECIMENS

100X Polarized Light N29519

250X Bright Field N29520

a. Gamma-Quenched Uranium-12 w/o Molybdenum Heat Treated for 1 Hr at 800 C and Water Quenched (Heat Treatment G)

100X Bright Field N29521

250X Bright Field N29522

b. Transformed Uranium-12 w/o Molybdenum Heat Treated for 1 Hr at 800 C, Furnace Cooled to 500 C, Held 2 Weeks, and Furnace Cooled (Heat Treatment M)

FIGURE 7. GAMMA-QUENCHED SPECIMENS AND TRANSFORMED SPECIMENS OF URANIUM-12 w/o MOLYBDENUM

HOT HARDNESS

The strength of uranium is affected by the amount of alloy materials added. In the case of uranium-zirconium and uranium-molybdenum alloys, an indication of the relative high-temperature strengths of these materials was obtained through measurements of hot hardness. The ease with which values may be obtained over a wide range of temperature makes this method practical for evaluating various compositions and heat treatments.

In this study, hot-hardness values were obtained on uranium-3 through 20 w/o zirconium and uranium 3.5 through 12.0 w/o molybdenum alloys. In the uranium-zirconium series, values were obtained for four different conditions of heat treatment, while in the uranium-molybdenum series hardness values of alloys in two heat-treated conditions were obtained.

Table 3 lists data on hardness of uranium-zirconium alloys at room temperature and at selected temperatures in the range between 600 and 800 C. The numbers reported are the average of three to five readings at each temperature. Where no numbers are given, the readings were inconsistent or were not obtained because of insufficient specimen.

From Table 3 it is apparent that some heat treatments have pronounced effects upon hot-hardness values of uranium-zirconium alloys. An example of this is the greatly improved hardness of uranium-3 w/o zirconium between 700 and 750 C when slowly cooled through the gamma transformation (Heat Treatment E on Table 3). The room-temperature hardness of alloys water quenched from 800 C is much greater than hardnesses obtained by any other method of heat treatment investigated.

Further investigation of the table reveals that above 700 C, an increase in hardness is accomplished by increasing the zirconium content. This condition continues until approximately 15 w/o zirconium has been added. Between 15 and 20 w/o addition of zirconium, the hardness of the resultant alloy is decreased at temperatures above 700 C. This suggests that the greatest high-temperature strength of uranium-zirconium in the range studied is in the vicinity of 15 w/o zirconium.

Table 4 lists room-temperature and hot hardness of uranium-molybdenum alloys between 600 and 800 C. The alloys were heat treated to obtain retained- and nearly transformed-gamma structures. Transformed structures were produced in specimens by allowing them to soak for a period of time at 500 C. In general, the period of time required for transformation was increased by increasing the molybdenum content of the alloys.

TABLE 3. HOT-HARDNESS DATA ON URANIUM-ZIRCONIUM ALLOYS

Zirconium Content (Balance Uranium), w/o	Heat Treatment ^(a)	Hardness, DPH, kg per mm ²							
		Room Temperature	600 C	650 C	680 C	700 C	725 C	750 C	800 C
3.0	A	285	67	36	29	5.1	2.3	2.2	--
3.0	F	473	48.2	26.3	13.3	4.1	2.4	2.6	2.1
3.0	E	266	49.0	27.6	9.3	15.7	13.1	10.9	--
3.0	CDD	269	47.5	35.0	22.8	4.7	2.4	1.6	--
5.0	A	336	42	34	10.7	6.0	5.4	4.5	--
5.0	F	513	44.5	26.7	7.0	6.6	5.9	4.7	3.0
5.0	E	295	37.2	35.3	19.5	7.7	6.0	5.2	--
5.0	CDD	316	49.8	36.2	22.5	4.4	2.6	2.7	2.7
7.0	A	352	--	31.0	11.7	9.0	8.0	7.1	4.8
7.0	F	420	--	--	10.6	9.3	8.7	7.2	4.9
7.0	E	306	--	--	12.8	10.8	8.5	7.7	5.9
7.0	CDD	338	45.9	37.8	13.0	5.8	6.4	5.0	3.6
10.0	A	364	53.0	23.0	7.6	14.2	12.3	9.9	--
10.0	F	540	49.0	26.5	13.4	13.7	11.0	8.2	--
10.0	E	312	39.7	30.7	27.3	4.3	2.5	2.3	1.8
10.0	CDD	341	46.5	33.9	9.8	16.0	12.8	8.7	--
15.0	A	372	71	28	15.0	17.5	14.9	12.4	--
15.0	F	462	43.8	32.3	15.8	15.5	13.9	11.3	7.0
15.0	E	317	63.9	30.9	15.5	19.5	15.4	13.6	9.6
15.0	CDD	350	84.2	43.5	23.8	21.5	17.6	13.3	--
20.0	A	377	69	25.0	16.6	15.7	13.6	10.7	--
20.0	F	393	48.8	26.9	15.5	14.9	13.6	10.7	6.7
20.0	B	353	74.9	31.7	19.0	18.0	13.6	12.6	--
20.0	C	343	--	36.0	17.5	17.6	14.9	11.0	7.1

(a) Heat Treatments:

- A. 1 hr at 800 C, furnace cooled.
- B. 1 hr at 800 C, furnace cooled to 750 C; between 750 C and 570 C cooled at rate of 1/2 C per min.
- C. 1 hr at 800 C, 2 hr at 550 C, water quench.
- CDD. 1 hr at 800 C, 2 hr at 550 C, water quenched; 5 min at 780 C, 2 hr at 550 C, and water quenched. Last step repeated.
- E. 1 hr at 800 C, furnace cooled to 670 C, held 24 hr, and furnace cooled.
- F. 1 hr at 800 C, water quenched, reheated to 670 C for 24 hr, furnace cooled.

TABLE 4. HOT HARDNESS OF URANIUM-MOLYBDENUM ALLOYS

Molybdenum Content (Balance Uranium), w/o	Heat Treatment(a)	Hardness, DPH, kg per mm ²							
		Room Temperature	600 C	650 C	680 C	700 C	725 C	750 C	800 C
3.5	G	260	15.4	4.4	--	3.2	--	1.3	3.8
3.5	H	438	31.0	9.2	11.7	10.8	9.2	6.1	4.4
5.0	G	119	26	19.0	--	13.2	--	9.3	7.5
5.0	J	397	14.3	12.5	11.4	11.1	9.6	8.6	7.1
7.0	G	248	34	35	--	24	--	17.4	14.8
7.0	K	448	47.2	38.1	34.0	31.4	23.9	20.6	13.3
9.0	G	276	89	69	--	51	--	38	30
9.0	L	423	86.9	78.3	65.3	58.2	48.3	41.1	27.7
12.0	G	310	122	92	--	72	--	49	37.0
12.0	M	312	158	112	105	93.0	78.8	67.4	47.4

(a) Heat Treatment:

G. 1 hr at 800 C, water quenched.

H. 1 hr at 800 C, air cooled, specimen protected in an evacuated glass envelope.

J. 1 hr at 800 C, furnace cooled to 500 C, held 24 hr, furnace cooled.

K. 1 hr at 800 C, furnace cooled to 500 C, held 100 hr, furnace cooled.

L. 1 hr at 800 C, furnace cooled to 500 C, held 200 hr, furnace cooled.

M. 1 hr at 800 C, furnace cooled to 500 C, held 2 weeks, furnace cooled.

The room-temperature hardnesses of transformed uranium-molybdenum alloys are greater than those of similar alloys containing retained-gamma structures. In addition, transformed uranium-3.5, 7, 9, and 12 w/o molybdenum alloys are harder, especially in the 650 to 750 C range, than the same alloys when possessing retained-gamma structures. This condition does not exist in the uranium-5 w/o molybdenum alloy, as this alloy is harder with a retained-gamma structure.

Hardness curves plotted on semilog paper appear in the Appendix of this report. The curves are given for uranium-zirconium alloys in one condition of heat treatment, and for uranium-molybdenum alloys in two conditions of heat treatment.

LINEAR THERMAL EXPANSION

The linear thermal expansion of uranium-zirconium and uranium-molybdenum alloys was studied in the temperature range of 20 to 950 C. Measurements were obtained by means of a recording quartz-tube dilatometer upon specimens protected by a vacuum of approximately 2×10^{-5} mm of mercury. The maximum heating and cooling rates to which specimens were subjected were about 5 C per min. In most cases only one thermal cycle was run. However, a second thermal cycle was used as a check on a few specimens.

Table 5 lists heating and cooling information obtained on specimens of both alloys between 20 and 950 C. Temperatures at the beginning and end of the transformations are given where detected. As transformation of uranium-molybdenum alloys became sluggish with increased molybdenum content, dilation-curve transformations were not detected on all specimens.

A few general characteristics were noted concerning dilation of uranium-zirconium and uranium-molybdenum alloys. They are mentioned in the following paragraphs.

Transformations were detected on all specimens of uranium-zirconium regardless of prior heat treatment and were easily detected both in the heating and cooling cycles. It appeared that thermal expansion was more a function of zirconium content than of heat treatment, as expansion of the same order of magnitude occurred in a given composition in both heat-treated conditions studied.

All uranium-zirconium specimens were reduced in length slightly as a result of having been cycled to 950 C. This is recorded on the dilation graphs by the cooling curve which falls below the base line. Increased zirconium in uranium caused decreased total linear expansion. In addition, a greater transformation-temperature span was produced by an increase in zirconium content. The last-mentioned phenomenon is most pronounced in the uranium-15 and 20 w/o zirconium alloys.

Dilation of uranium-molybdenum alloys was measured in two conditions of heat treatment. Included were alloys both gamma quenched and partially transformed. The results are shown in Table 5 and by graphs included in the Appendix.

Transformation was detected only upon uranium-3.5 and 5 w/o molybdenum gamma-quenched alloys. However, when soaked for a period of time at 500 C, uranium-7 and 9 w/o molybdenum specimens were observed to transform during the heating cycle. Whenever transformation was detected in uranium-molybdenum alloys, it was accompanied by a slight increase in specimen length. Where transformation was not detected, the specimens decreased slightly in length upon cycling to 950 C. Over-all contraction of uranium-molybdenum alloys was less than that occurring in uranium-zirconium alloys.

THERMAL CYCLING

Cylinders of the uranium-zirconium and uranium-molybdenum alloys under investigation were thermal cycled to determine their relative thermal stabilities. The cylinders, measuring approximately 1.00 in. long and 0.425 in. in diameter, were sealed in individual Vycor capsules under a partial pressure of argon.

Uranium-zirconium specimens were cycled at two temperatures: between 150 and 680 C, and between 150 and 725 C. The uranium-molybdenum alloys were cycled only at the higher temperature. Time required for completing one 150 to 725 C cycle was approximately 25 min.

The uranium-zirconium alloys withstood cycling well between 150 and 680 C. Even when cycled for more than 500 times, specimens were observed to have changed less than 0.1 per cent in length per 100 thermal cycles. In addition, surface condition and appearance of the specimens were good. It appeared that specimens containing the greater zirconium contents were least affected by cycling deformation.

TABLE 5. LINEAR THERMAL EXPANSION OF URANIUM-

Nominal Composition (Balance Uranium), w/o	Heat Treatment ^(a)	Cycles	Coefficient of Linear Expansion $\times 10^6$ Over Tem -						
			20-100	20-200	20-300	20-400	20-500	20-600	20-700
3.5Mo	G	2	10.85	12.64	13.71	14.47	15.19	16.27	21.50
			13.29	13.86	14.42	15.17	15.97		22.15
3.5Mo	H	2	11.90	13.38	14.30	14.99	15.78	16.74	
			14.41	13.97	14.80	15.32	15.96		21.79
5.0Mo	G	3	13.20	14.07	15.46	16.26	16.56	17.08	21.06
			14.15	14.20	14.50	14.91	16.59	19.96	19.81
5.0Mo	J	1	11.64	13.18	14.13	14.66	15.30		20.54
			12.85	13.78	14.38	14.91		19.76	19.69
7.0Mo	G	1	10.43	11.26	12.42	13.60	14.23	14.73	15.26
			12.78	13.13	12.66	14.18	14.88	15.45	15.96
7.0Mo	K	1	12.24	13.14	14.13	14.87	15.66	16.37	19.97
		2	11.73	12.47	13.09	13.60	13.88	14.38	15.01
9.0Mo	G	1	12.88	13.42	14.11	14.68	15.22	15.74	16.07
			11.80	12.09	12.86	13.61	14.08	14.52	15.04
9.0Mo	L	1	9.99	11.49	12.63	13.36	14.05		16.92
			11.86	12.57	13.00	13.56	14.08	14.57	15.09
12.0Mo	G	2	8.95	10.45	11.59	12.11	12.56	13.08	13.56
			11.34	11.70	12.22	12.73	13.19	13.69	14.14
12.0Mo	M	1	13.76	13.75	14.01	14.11	14.25	14.41	14.59
			11.74	12.46	12.75	13.34	13.82	14.23	14.75
3.0Zr	E	2	13.49	14.48	15.18	15.91	16.74	17.83	
			14.70	15.21	15.70	16.65	17.69	19.13	
3.0Zr	CDD	1	13.63	14.83	15.44	15.92	16.62	17.89	
			14.31	15.27	15.78	16.58	17.70	19.90	
5.0Zr	E	1	13.38	13.57	14.53	15.22	16.07	17.15	
			14.46	15.11	15.53	16.18	17.22	18.58	26.50
5.0Zr	CDD	1	11.54	13.15	14.36	14.99	15.71	17.12	
			13.54	14.52	14.99	15.84	16.81	18.30	26.00
7.0Zr	E	1	10.24	11.89	13.52	14.59	15.52	16.47	
			13.03	13.66	14.19	14.86	15.78	17.16	24.70

ZIRCONIUM AND URANIUM-MOLYBDENUM ALLOYS

Temperature, C, Ranges Shown				Temperature at Beginning of Transformation, C	Coefficient x 10 ⁶ at Beginning of Transformation	Temperature at Finish of Transformation, C	Coefficient x 10 ⁶ at Finish of Transformation
20-800	20-900	20-950	20-1000				
21.36	21.36	21.43		600	16.27	680	21.46
22.01	21.98	21.98		575	17.50	605	22.29
21.80	21.66	21.64		625	17.60	685	21.90
21.71	21.77	21.81		550	16.88	625	21.96
20.84	20.85	20.87		625	17.99	675	21.08
19.87	20.08	20.15		500	16.59	565	19.95
20.29	20.27	20.28		575	15.79	650	20.53
19.81	20.02	20.06		445	15.51	575	19.83
15.78	16.17	16.24					
16.45	17.04	17.34					
19.74	19.70	19.76		600	16.37	665	20.02
15.67	16.14	16.37					
16.27	16.39	16.36					
15.71	16.40	16.74					
17.13	17.44	17.51		595	14.44	650	16.14
15.62	16.26	16.51					
14.14	14.71	--	15.25				
14.69	15.27	--	15.90				
14.82	15.26	15.49					
15.28	15.89	16.25					
24.39	23.95	23.83		680	19.46	750	24.63
25.59	25.33	25.21		650	20.15	680	26.36
22.79	22.57	22.56		685	19.42	720	23.11
25.59	25.24	25.12		660	20.30	680	26.19
23.17	22.90	22.84		685	19.00	725	23.48
25.95	25.53	25.40		650	19.70	675	226.73
23.73	23.23	23.10		695	19.23	715	24.46
25.46	25.17	25.04		650	19.45	670	26.17
22.08	21.51	21.38		690	18.89	720	22.88
24.28	24.13	24.08		655	18.81	670	24.82

TABLE 5.

Nominal Composition (Balance Uranium), w/o	Heat Treatment(a)	Cycles	Coefficient of Linear Expansion $\times 10^6$ Over Tem-						
			20-100	20-200	20-300	20-400	20-500	20-600	20-700
7.0 Zr	CDD	1	11.29	12.58	13.81	14.31	15.06	16.25	
			12.38	13.25	13.85	14.45	15.41	16.85	24.29
10.0 Zr	E	1	10.51	12.02	13.57	14.85	15.69	16.43	
			13.83	13.91	13.94	14.33	15.24	16.66	24.45
10.0 Zr	B	1	13.88	14.26	15.12	15.82	16.41	17.17	
			12.38	13.03	13.37	13.96	14.94	16.32	24.00
15.0 Zr	B	1	12.20	11.73	12.90	13.79	14.59	15.41	19.58
			10.70	11.71	12.38	13.02	14.00	15.42	21.45
15.0 Zr	E	1	10.79	11.51	12.54	13.33	14.31	15.20	
			10.44	11.25	11.80	12.67	13.73	15.04	20.86
20.0 Zr	C	2	10.26	11.09	12.04	12.68	13.43	14.42	
			10.04	10.72	11.30	11.97	12.91	14.22	18.35
20.0 Zr	B	2	9.30	10.60	11.48	12.17	12.90		
			10.08	11.04	11.60	12.45	13.43	14.62	18.32

Note: The first row of coefficients, opposite the specimen, are from the heating curve and the second row are from the cooling curve.

(a) Heat Treatments:

- G. 1 hr 800 C, water quenched.
- H. 1 hr 800 C, air cooled, specimen protected in evacuated glass envelope.
- J. 1 hr 800 C, furnace cooled to 500 C, held 24 hr, furnace cooled.
- K. 1 hr 800 C, furnace cooled to 500 C, held 100 hr, furnace cooled.
- L. 1 hr 800 C, furnace cooled to 500 C, held 200 hr, furnace cooled.
- M. 1 hr 800 C, furnace cooled to 500 C, held 2 weeks, furnace cooled.
- C. 1 hr 800 C, isothermally transformed 550 C for 2 hr, water quenched.
- E. 1 hr 800 C, held 24 hr 670 C, furnace cooled.
- CDD. 1 hr 800 C, isothermally transformed 2 hr 550 C; plus 5 min 780 C, isothermally transformed 2 hr 550 C, plus repeat 5 min 780 C, 2 hr 550 C.
- B. 1 hr 800 C, furnace cooled to 750 C, furnace cooled from 750 C to 570 C at 1/2 C per min.

(Continued)

Temperature, C, Ranges Shown				Temperature at Beginning of Transformation, C	Coefficient x 10 ⁶ at Beginning of Transformation	Temperature at Finish of Transformation, C	Coefficient x 10 ⁶ at Finish of Transformation
20-800	20-900	20-950	20-1000				
21.57	20.77	20.46		690	18.49	710	22.65
23.92	23.73	23.64		650	18.50	670	24.47
22.90	22.08	21.78		690	19.15	720	23.59
24.17	24.00	23.96		645	18.57	665	24.27
23.47	22.87	22.64		685	19.64	725	24.09
23.69	23.53	23.46		645	18.27	665	23.79
19.63	19.18	19.06		625	15.88	700	19.58
22.18	21.55	21.64		600	15.42	665	20.82
19.73	19.24	18.95		630	15.73	730	19.80
20.86	20.92	21.03		610	15.21	690	20.79
17.56	17.47	17.41		625	14.81	710	17.40
18.51	18.63	18.64		600	14.22	680	18.29
16.65	16.37	16.19		620	14.08	720	16.74
18.38	18.50	18.60		600	14.62	665	18.30

The uranium-zirconium specimens were also cycled between 150 and 725 C. When examined after 60 cycles, specimens of lower zirconium contents showed evidence of surface roughening and blistering. This condition continued upon subsequent cycling. Specimens of higher zirconium content were also affected as the number of thermal cycles was increased. At the end of 250 cycles, roughening and distortion had occurred in specimens of uranium-3 through 10 w/o zirconium to the extent that accurate measurements could not be obtained. The surface of the uranium-15 and 20 w/o zirconium specimens was smooth but had become symmetrically distorted as a result of cycling. Figure 8a shows a uranium-10 w/o zirconium specimen cycled 530 times between 150 and 680 C. It is only slightly affected by thermal cycling. Figure 8b shows the same composition cycled 235 times between 150 and 725 C. Both specimens were machined from the same material and both received the same heat treatment. The distortion present in the specimen in Figure 8b is a result of cycling beyond the alpha-beta transformation.

Uranium-molybdenum alloys were thermally cycled in two conditions of heat treatment. The specimens were examined after 250 and 530 cycles, respectively. At the end of 530 cycles, the specimens were examined for deformation and growth. All of the specimens appeared little affected by cycling, with the exception of uranium-3.5 w/o molybdenum. This specimen was surface roughened and distorted, and appeared to be breaking down. The remainder of the cylinders possessed smooth surfaces and a good appearance. Change in length and diameter of these specimens was less than 0.1 per cent per 100 cycles.

Figure 9a shows a uranium-3.5 w/o molybdenum specimen after 530 cycles. Figure 9b shows a specimen of uranium-7.0 w/o molybdenum cycled the same amount. The clean appearance of the uranium-7 w/o molybdenum specimen is typical of specimens of higher molybdenum content after cycling 500 times.

CONCLUSIONS

On the basis of physical-property determinations listed in this report, primary uranium alloys containing 5 through 12 w/o molybdenum appear promising as potential reactor fuels. The alloys are more thermally stable at temperatures above 680 C than comparable uranium-zirconium alloys. In addition, hot-hardness values obtained between 600 and 800 C indicate that the uranium-molybdenum alloys possess greater elevated-temperature strengths than the zirconium alloys.

2-1/2X

N29523

a. Cycled 530 Times Between 150 and 680 C

2-1/2X

N29524

b. Cycled 235 Times Between 150 and 725 C

FIGURE 8. URANIUM-10 w/o ZIRCONIUM THERMALLY
CYCLED AS INDICATED

Specimens were furnace cooled from 800 C.

2-1/2X

N29525

a. Uranium-3.5 w/o Molybdenum

2-1/2X

N29526

b. Uranium-7 w/o Molybdenum

FIGURE 9. URANIUM-MOLYBDENUM SPECIMENS CYCLED
530 TIMES BETWEEN 150 AND 725 C

Specimens were water quenched from 800 C.

Binary uranium-zirconium alloys below 15 w/o zirconium were shown to have poor thermal stability above 680 C. However, alloys containing 15 and 20 w/o zirconium possessed a degree of stability and an elevated-temperature hardness sufficient to warrant further study concerning their use as reactor fuels.

Studies are in progress to obtain elevated-temperature mechanical properties on both uranium-molybdenum and uranium-zirconium alloys. This information will be reported as it becomes available.

APPENDIX

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A-1

FIGURE A-1. LINEAR THERMAL EXPANSION VERSUS TEMPERATURE FOR URANIUM-3.5 w/o MOLYBDENUM

A-18912

A-18913

FIGURE A-2. LINEAR THERMAL EXPANSION VERSUS TEMPERATURE FOR URANIUM-5.0 w/o MOLYBDENUM

A-18914

FIGURE A-3. LINEAR THERMAL EXPANSION VERSUS TEMPERATURE FOR URANIUM-7.0 w/o MOLYBDENUM

A-18915

FIGURE A-4. LINEAR THERMAL EXPANSION VERSUS TEMPERATURE FOR URANIUM-9.0 w/o MOLYBDENUM

FIGURE A-5. LINEAR THERMAL EXPANSION VERSUS TEMPERATURE FOR URANIUM-12.0 w/o MOLYBDENUM

A-18916

A-18917

FIGURE A-6. LINEAR THERMAL EXPANSION VERSUS TEMPERATURE FOR URANIUM-3.0 w/o ZIRCONIUM

FIGURE A-7. LINEAR THERMAL EXPANSION VERSUS TEMPERATURE FOR URANIUM-5.0 w/o ZIRCONIUM

A-18919

FIGURE A-8. LINEAR THERMAL EXPANSION VERSUS TEMPERATURE FOR URANIUM-7.0 w/o ZIRCONIUM

FIGURE A-9. LINEAR THERMAL EXPANSION VERSUS TEMPERATURE FOR URANIUM-10.0 w/o ZIRCONIUM

A-18920

FIGURE A-10. LINEAR THERMAL EXPANSION VERSUS TEMPERATURE FOR URANIUM-15.0 w/o ZIRCONIUM

A-18921

FIGURE A-11. LINEAR THERMAL EXPANSION VERSUS TEMPERATURE FOR URANIUM-20.0 w/o ZIRCONIUM

A-18922

A-18923

FIGURE A-12. HOT HARDNESS OF URANIUM-MOLYBDENUM ALLOYS

A-18924

FIGURE A-13. HOT HARDNESS OF URANIUM-MOLYBDENUM ALLOYS
GIVEN HEAT TREATMENT G

A-18926

FIGURE A-14. HOT HARDNESS OF URANIUM-ZIRCONIUM ALLOYS
GIVEN HEAT TREATMENT A