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CREEP STRENGTH OF URANIUM ALLOYS AT 1500 AND 1800 F

by

H. A. Saller
J. T. Stacy
N. S. Eddy
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For The Atomic Energy Commission

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Chief, Declassification Branch

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ABSTRACT

The creep resistance of various uranium binary alloys was investigated at 1500° and 1800°F in vacuum. Tests were made on alloys of uranium with beryllium, columbium, molybdenum, tantalum, titanium, and zirconium and on molybdenum- UO_2 composites. Of the alloys examined, those of the uranium-molybdenum system exhibited the best creep resistance. At 1500°F, creep rates of about 0.005%/hr were produced in uranium-molybdenum alloys by a stress of 2500 psi and, at 1800°F, similar creep rates were obtained in composites of 90 wt % molybdenum-10 wt % UO_2 by a stress of 12,000 psi.

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ABSTRACT

The creep resistance of various uranium binary alloys was investigated at 1500° and 1800°F in vacuum. Tests were made on alloys of uranium with beryllium, columbium, molybdenum, tantalum, titanium, and zirconium and on molybdenum- UO_2 composites. Of the alloys examined, those of the uranium-molybdenum system exhibited the best creep resistance. At 1500°F, creep rates of about 0.005%/hr were produced in uranium-molybdenum alloys by a stress of 2500 psi and, at 1800°F, similar creep rates were obtained in composites of 90 wt % molybdenum-10 wt % UO_2 by a stress of 12,000 psi.

INTRODUCTION

With considerable interest centered in the utilization of uranium-bearing metallic fuel elements at high temperatures, a program was initiated to determine the high-temperature creep characteristics of potential fuel element alloys. The immediate objective was a screening of various uranium-alloy systems. Binary alloys of uranium with beryllium, columbium, molybdenum, tantalum, titanium, and zirconium, and composites of molybdenum and uranium dioxide were considered for investigation. Of these materials, the uranium-molybdenum, uranium-titanium, and uranium-zirconium alloys received substantial study, while the columbium and tantalum alloys and the molybdenum-uranium dioxide composites received a more cursory examination.

Although screening tests were planned at a stress of 5000 psi in the temperature range 1500 to 2200 F, considerably lower stresses were found to produce excessive creep rates in most cases. Consequently, much lower stresses were used and these at the lower end of the temperature range. Tests were carried out at 1500 or 1800 F in vacuum, with limits being loosely set at a few per cent elongation or two to three hundred hours in test. The target was one per cent elongation in 200 hr or a creep rate of 0.005 %/hr.

EXPERIMENTAL WORK

General Methods

Specimen Preparation

To facilitate fabrication, the creep testing equipment was designed to use a 3-in. creep specimen which is illustrated in Figure 1. The general methods of preparing and creep testing the uranium alloys are discussed in the following paragraphs, but details of the preparation, where they differ, are reported in those sections relating to the specific alloys.

The materials used in the processing consisted of the following: beryllium, Brush QMV grade; columbium, Fansteel scrap sheet or 325-mesh powder; molybdenum, Fansteel scrap sheet or 325-mesh powder; tantalum, Fansteel scrap sheet or 325-mesh powder; titanium, Bureau of Mines; uranium, Hanford slugs; and zirconium, Foote crystal bar.

FIGURE 1. TYPE OF CREEP SPECIMEN USED IN THE HIGH-TEMPERATURE TESTING OF URANIUM ALLOYS

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Both casting and powder-metallurgy techniques were employed in obtaining the uranium alloys. During the course of the investigation additional facilities became available for the casting of these materials, viz., a larger capacity inert-atmosphere arc-melting furnace and a low-frequency induction vacuum furnace. These improved the quality and increased the production of alloys for testing during the latter stages of the research. The equipment used for melting consisted of the following:

1. An induction-type bottom-pour vacuum or helium-atmosphere furnace with graphite crucible and mold having a 300,000 to 500,000 cycles per second electronic (Megatherm) power source.
2. An induction-type bottom-pour vacuum furnace with graphite crucible and mold having a 3,000 cycles per second motor-generator-set power source.
3. An inert-atmosphere tungsten-electrode arc furnace with a water-cooled copper-block crucible of 7.5 cm³ capacity having a motor-generator-set power source of 450 amp.

4. An inert-atmosphere tungsten-electrode arc furnace with a water-cooled copper-block crucible of 32 cm³ capacity having a motor-generator-set power source of 800 amp.

The production of creep specimens, particularly uranium-molybdenum alloys, by powder-metallurgy methods was based on the use of mixtures of minus 325-mesh powders of the alloying element and a uranium master alloy. To prepare the latter, arc melts of uranium binary alloys were chipped and ball milled under an argon atmosphere. Samples were prepared by mixing the powders for two hours in a mixing box, adding a Carbowax binder, and hydrostatically pressing at 100,000 psi. This method of pressing produced a green compact of more uniform density than that usually obtained with conventional steel dies. Briefly, this pressing procedure involved loading the mixed powders into a rubber-lined perforated metal tube, plugging the open ends with rubber stoppers, and subjecting the entire assembly to hydrostatic pressure. Green compacts were sintered for periods up to 100 hr in vacuum at temperatures between 2100 and 2400 F. Also, two impregnation methods were investigated. These are discussed in the section dealing with uranium-molybdenum alloys.

As-cast, as-swaged, or as-rolled material was creep tested. Where possible, the alloys were tested in the hot-rolled condition, the alloys being rolled bare, or in steel or molybdenum jackets. In some instances, the alloys were jacketed and swaged. A helium-atmosphere furnace was used for heating those alloys which were worked bare to minimize the heavy oxidation.

Because of the tendency of most uranium alloy castings to segregate, with the heavier uranium concentrating in the bottom of the mold and the lighter element at the top, chemical analyses were made of the gage sections of the tested creep specimens rather than of the castings or rolled bars themselves. Some success was achieved in reducing the segregation by remelting the first casting in an inverted position or by chill casting in a copper rather than a graphite mold. Of the two methods, the first was more effective, but resulted in additional carbon pickup from the graphite crucible.

Creep Testing

For the creep testing of the uranium alloys at 1500 and 1800 F in vacuum, two furnaces were used. These consisted essentially of wire-wound (Chromel) central tubes shielded from exterior water-cooled brass shells by concentric stainless steel baffles. Metal expansion bellows provided for the movement of the specimen adapters, while suitable windows permitted observation of the heated specimens. A vacuum of 1 to 5

microns was maintained during test and the specimen temperature was controlled to within ± 3 F.

In testing, the stress was applied within 2 or 3 hr after the specimen had reached temperature, and extensometer readings were made periodically thereafter until rupture occurred or the elongation was sufficient to warrant discontinuance. In some instances, where the elongation was insignificant, the stress was raised periodically to obtain successively higher creep rates. The extensometer readings were taken on ruled platinum reference strips attached to the gage sections of the specimens; a filar micrometer microscope with a sensitivity of 0.00005 in. was used. In cases where fogging of the observation windows occurred, an external dial gage was substituted. The data obtained in this manner were converted to percentages and plotted as time-deformation curves. These are presented in the Appendix.

Results and Discussion

Most of the vacuum creep tests of the uranium alloys were carried out at a temperature of 1500 F and at an initial stress level of 500 psi. Under these conditions, all of the uranium-titanium and uranium-zirconium alloys elongated 1 per cent in less than 200 hr, while, in a similar period, several of the uranium-molybdenum and one of the uranium-tantalum alloys showed less than 1 per cent elongation. Creep-rate data obtained at 1500 F for two of the better uranium-molybdenum alloys indicate that a load of 2500 psi would be required to produce an elongation of 1 per cent in 200 hr. The elevated-temperature strength of uranium-columbium alloys could not be judged adequately on the basis of the few tests made. Molybdenum- UO_2 composites were tested in vacuum at 1800 F and those containing 10 wt % UO_2 did not elongate more than 1 per cent in 200 hr under a load of 12,000 psi.

In this survey, no deliberate effort was made to determine the effect of fabrication conditions on the creep strength of the alloys. The lack of duplicate test results, especially in the uranium-molybdenum and uranium-tantalum systems, indicates that the 1500 F creep strength of these alloys may be influenced markedly by the method or conditions of fabrication. Also, the possibility of precipitation strengthening, which might be feasible in certain uranium alloys containing molybdenum, tantalum, or titanium, was not investigated.

The results of all completed creep tests are tabulated in the Appendix, together with time-deformation curves which illustrate the elongation of the specimens under stress. The preparation, testing, and general behavior of the alloys are discussed in the following sections.

Uranium-Molybdenum Alloys

Creep-strength data for uranium-molybdenum alloys at 1500 F in vacuum at a stress of 500 psi are given in Table A-1. Figures A-1 and A-2 show time-deformation curves for the cast and the hot-rolled alloys, respectively. Similar curves for one cast and one rolled alloy which showed exceptional strength at 1500 F are presented in Figure A-3 along with creep-rate data for stresses up to 3,000 psi, the stress levels having been increased incrementally during the time of test.

From these data, it will be observed that the creep resistance of the rolled alloys at 1500 F improved rapidly with increasing molybdenum content over the workable range. The cast alloys, on the other hand, behaved more erratically and showed only a general trend toward greater strength with increased molybdenum content. None of the cast alloys showed strength superior to that evinced by the best of the rolled alloys; however, no study of the effects of variables in the casting conditions on the creep resistance was attempted. In general, it would appear from these limited data that, insofar as the uranium-rich alloys are concerned, the maximum high-temperature strengthening effect is obtained within the solid solution (gamma) field.

Several methods were used in preparing uranium-molybdenum alloys. In casting alloys relatively low in molybdenum, double induction melting in graphite was fairly successful using a charge of the primary elements, the ingot being remelted in an inverted position. For alloys containing from 15 to 35 wt % molybdenum, the best results were secured when the charge was made up of 50 wt % molybdenum-50 wt % uranium arc-melted alloy buttons together with excess uranium metal. At higher percentages, 50, 70, and 90 wt % molybdenum, crushed arc-melted alloy buttons were charged and melting was carried out in zirconia crucibles. However, induction-coil arcing limited the temperatures obtainable, and castings of these higher molybdenum alloys were porous, segregated, or incompletely melted. Several different molds were tried, the best results being obtained with a graphite mold having a taper of about 1-3/4 in./ft.

Alloys containing up to 15 wt % molybdenum were amenable to hot working. Attempts to hot work alloys containing more molybdenum were unsuccessful; e. g., a 28 wt % molybdenum alloy could not be forged bare at 1850 or 2200 F, or swaged at 2000 F, and 34 wt % molybdenum alloys, canned in molybdenum, broke up during rolling at 2200 F. In view of these and other results, the hot-working range of uranium-rich uranium-molybdenum alloys appears to be confined to the single-phase gamma field.

Considerable effort was directed toward producing molybdenum-rich molybdenum-uranium alloys, principally of 55 and 78 wt % molybdenum

content, by powder-metallurgy methods using mixtures of molybdenum and uranium-molybdenum arc-melted alloy powders. Although short-time high-temperature sintering in the presence of a liquid phase was attempted, sintering temperatures were confined generally to a maximum of 2100 F, since sintering for any length of time at higher temperatures resulted in melting and gravity separation of the much heavier uranium-rich phase. Metallographic examination of these sintered alloys showed them to consist of molybdenum-rich grains partially surrounded by the uranium-rich phase. Of three sintered specimens creep tested at 1500 F in vacuum under a stress of 500 psi, two broke on loading and the third fractured after 2 hr, with only 0.2 per cent elongation.

On the basis of such creep and metallographic data, it was concluded that the sintered two-phase structure was inherently weak. To form a more favorable structure, two other fabrication methods were investigated, viz., the impregnation of porous sintered molybdenum-powder compacts with molten uranium and the hot rolling of jacketed sintered bars. Two methods of infiltration were explored. The first consisted of infiltrating sintered molybdenum skeletons of various porosities by vacuum furnace melting uranium or uranium-molybdenum alloys placed on the compacts, while the second consisted of holding a sintered skeleton in a bath of molten uranium. Impregnation occurred in both processes, but the resultant specimens were not suitable for creep work. Of the two methods, the first appeared to offer some promise, but required considerable additional experimentation to develop a suitable technique for the production of creep specimens. The hot rolling of jacketed sintered bars was not successful at 55 and 78 wt % molybdenum content.

Uranium-Titanium Alloys

Compositions across the entire uranium-titanium system were easily fabricated, the principal problem being segregation. Alloys were rolled or forged without jacketing between 1500 and 1800 F. Hot rolled bars near the compound composition (U_2Ti) could not be water quenched to prevent oxidation during cooling because of cracking.

These alloys were creep tested at 1500 and 1800 F in vacuum under a stress of 500 psi. Because of the extremely rapid elongation at 1800 F, only the three initial tests were made at that temperature. At 1500 F and 500 psi stress, all specimens, with one exception, elongated 1 per cent in less than 50 hr. The best creep resistance was shown by alloys containing between 17 and 37 wt % titanium, which corresponds at 1500 F to the two-phase $U_2Ti-Ti\beta$ field of the phase diagram. The presence of carbon in these alloys would cause them to be higher in compound than apparent from their chemical analyses. Test data are listed in Table A-2, and the corresponding time-deformation curves are shown in Figures A-4 and A-5.

Uranium-Zirconium Alloys

The fabricability of uranium-zirconium alloys of all compositions closely approximated that of the uranium-titanium alloys, the principal difficulty likewise being the minimization of segregation. The alloys were rolled, or forged and rolled, with or without jacketing at 1450 to 1550 F. Creep testing was carried out at 1500 and 1800 F in vacuum at a stress level of 500 psi, the alloys showing little strength at the higher temperature. At 1500 F, an alloy containing 47.1 wt % zirconium elongated 1 per cent in 57 hr. This alloy showed the best creep resistance of those tested. From the uranium-zirconium equilibrium diagram, it would appear that the strongest alloys at 1500 F lie in the zirconium-rich portion of the γ -field. Creep test results are given in Table A-3, and the time-deformation curves are shown in Figures A-6 and A-7.

Miscellaneous Uranium Alloys

Uranium alloys containing up to 20.3 wt % tantalum were prepared for creep testing by several different methods. One unusual procedure, which became feasible with the completion of a large-diameter arc-melting furnace, was to melt the alloys in a water-cooled copper crucible in the form of small wire bars from which specimens could be machined directly. Powder-metallurgy fabrication of these alloys was obstructed chiefly by the difficulty of preparing suitable high-tantalum master alloys for powdering. A 15 wt % tantalum-85 wt % uranium alloy powder was extremely pyrophoric.

Creep tests were made in vacuum at a stress of 500 psi at 1500 F, one test being conducted at 1800 F. The results of these tests are presented in Table A-4 and Figures A-8 and A-9. Only one specimen, Ta 1-2, containing 5.6 wt % tantalum, showed relatively good strength at 1500 F. No apparent reason can be assigned to account for this behavior other than that it was hot rolled or that chill casting plus subsequent hot working favored precipitation strengthening. Metallographic examination of this and other cast specimens showed the structures consisted of dispersions of tantalum, or a tantalum-rich phase, in matrices of substantially pure uranium. The very slight solubility of tantalum in gamma uranium would not favor solid solution strengthening.

The induction melting, in graphite crucibles, of uranium-columbium alloys containing appreciable amounts of columbium was generally unsuccessful when the primary metals were used as the charge. The addition of columbium in the form of pressed powder briquettes to increase the surface area exposed to the melt was not effective in increasing the solution rate. Preparation of these alloys by induction melting buttons of uranium-columbium master alloys previously prepared by arc melting was in progress when the program was terminated. The results obtained for three

low-columbium alloys, creep tested at 1500 F and 500 psi, are presented in Table A-4 and Figure A-10.

On the basis of the uranium-columbium phase diagram, it would appear that considerable solid solution strengthening of uranium might be expected in the broad gamma field, especially since it is known that the strength of columbium decreases relatively slowly with increasing temperature. The preparation of suitable specimens is potentially feasible by arc-melting methods, but it is likely that any further fabrication by hot working would have to be carried out at relatively high temperatures on jacketed alloys. A 50 wt % uranium-50 wt % columbium alloy prepared by arc melting could not be forged at 1550 F.

A uranium-beryllium alloy creep specimen of the compound composition (UBe₁₃), prepared by powder-metallurgy methods, was extremely brittle and cracked while being ground. This was the only composition investigated in this system.

Two ternary alloys, containing somewhat over 40 wt % uranium in combination with zirconium plus either titanium or tantalum as the third element, were creep tested at 1500 F in vacuum at a stress of 500 psi. In neither case did the alloy develop greater strength than the best binary uranium-zirconium alloy. The results of these tests are given in Table A-4 and Figure A-11.

Molybdenum-UO₂ Composites

Specimens of molybdenum-UO₂ composites for creep testing at 1800 F in vacuum were fabricated by several methods: hot swaging the green compacts in molybdenum jackets; low-temperature (3200 F) sintering of pressed compacts, jacketing in steel, and hot (2200 F) rolling; and double sintering (3200 and 3770 F) pressed compacts. All sintering was carried out in hydrogen. Sintered composites containing 20, 25, and 30 wt % UO₂ broke up on rolling and were increasingly brittle in the as-sintered condition, the as-sintered 30 wt % specimen fracturing during grinding.

The creep-test results for these composites are listed in Table A-5. Figure A-12 illustrates the behavior of these specimens under load. Hot-swaged Specimen J-138-2 was loaded incrementally to determine the approximate stress required to cause a 1 per cent deformation in 200 hr at 1800 F. Under a 12,000-psi load, hot-swaged Specimen J-138-4 elongated 1 per cent in 185 hr, while Specimen 76 in the rolled condition under the same stress showed little elongation prior to fracture at 289 hr. It is apparent from these data that high-strength uranium-bearing molybdenum-base materials can be fabricated, but that the uranium content is quite restricted.

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APPENDIX

TABLES OF RESULTS AND CREEP CURVES

Note: Values listed in the tables were taken from the original creep curves. Elongations were measured after rupture or on discontinuance of test. Time-deformation curves have been smoothed to a limited extent because of reduction in scale and to remove extreme irregularities in the vicinity of the origin when they occurred.

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TABLE A-1. CREEP DATA FOR URANIUM-MOLYBDENUM ALLOYS AT 1500 F IN VACUUM

Alloy	Composition, wt %			Condition	Stress, psi	Time for 1 Per Cent Deformation, hr	Minimum Creep Rate, %/hr	Test Time, hr ^(b)	Elonga- tion, %
	Nom- inal Mo	Analysis							
		Mo ^(a)	C						
<u>Rolled</u>									
M5-4	4.3	4.8	0.50	Induction melted and cast in graphite; rolled at 1650 F	500	1	2.16	6.9	15.1
L-5	10.0	7.5	0.13	Ditto	"	7	0.034	160.	4.5
L-11	10.0	7.8	0.13	"	"	2	0.052	166.	7.5
41-2	29.0	12.3	0.24	Induction melted and cast in graphite; canned and rolled at 2200 F	"	29	0.014	172.	3.6
39-6	12.0	13.3	0.10	Induction melted and cast in graphite; canned and rolled at 2000 F	"	> 330 ^(c)	0.00008 ^(c)	337 ^(c)	0.1 ^(c)
39-5	12.0	13.3	0.27	Ditto	"	150	0.0023	191	1.1
<u>Cast</u>									
59	12.0	10.6	0.24	Induction-melted arc melts; cast in graphite	500	314	0.0017	353	1.2
33	19.0	13.4	0.29	Ditto	"	47	0.0076	174	2.2
60-2	21.0	15.1	0.20	"	"	60	0.006	115	1.5
60-1	21.0	17.4	0.19	"	"	38	0.027	96	3.7
61-3	33.0	19.5	0.67	"	"	113	0.006	163	1.2
61-2	33.0	21.7	0.16	"	"	160	0.001	282	1.2
27	26.0	26.3	0.24	"	"	20	0.075	41	1.3
58	37.0	33.9	1.60	"	"	> 290 ^(c)	0.0008 ^(c)	290 ^(c)	0.6 ^(c)

(a) Molybdenum by difference except for alloys M5-4, L-5, and L-11, in which molybdenum was analyzed directly.

(b) All tests were discontinued before rupture.

(c) Stress subsequently raised in successive steps above 500 psi.

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TABLE A-2. CREEP DATA FOR URANIUM-TITANIUM ALLOYS AT
1500 AND 1800 F IN VACUUM

Alloy	Composition, wt %			Condition	Stress, psi	Time for 1 Per Cent Deformation, hr	Minimum Creep Rate, %/hr	Test Time, hr ^(b)	Elonga- tion, %
	Nom- inal Ti	Analysis							
		Ti ^(a)	C						
1500 F									
48	12.1	4.2	0.38	Induction melted and cast in graphite; rolled at 1800 F	500	0.7	0.14	30.9	6.4
Ti2-2	6.3	4.3	0.19	Induction melted and cast in copper mold(c); rolled at 1500 F	"	0.04	28.	0.4	11.0
35	20.0	9.3	0.22	Induction melted and cast in graphite; rolled at 1800 F	"	3.0	0.05	78.	4.6
30	20.0	12.3	0.25	Induction melted and cast in graphite; rolled at 1550 F	"	8.5	0.06	170.4	12.8
28	32.0	17.0	0.27	Ditto	"	35.	0.0034	211.	2.6
63	20.0	20.3	0.45	Induction melted and cast in graphite; rolled at 1800 F	"	23.	0.008	149.5	2.9
57	25.5	25.7	1.00	Ditto	"	163.	0.003	238.6	1.4
64	30.0	32.6	0.80	"(c)	"	40.	0.0045	167.7	2.2
36	32.0	37.2	0.32	"	"	44.	0.0032	197.	2.1
66	50.0	47.4	1.64	"(c)	"	9.5	0.06	111.8	7.4
Ti54	55.0	55.4	0.19	Arc melted; re- melted in BeO; forged and rolled at 1700 F	"	12.5	0.007	193.	3.7
Ti62	65.0	62.2	0.95	Ditto	"	10.5	0.017	116.	3.7
Ti75	75.0	75.6	0.49	"	"	<0.1	12.0	1.1	12.2
Ti90	90.0	90.6	0.28	"	"	1.7	0.4	44.7	9.4

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TABLE A-2 (Continued)

Alloy	Composition, wt %			Condition	Stress, psi	Time for 1 Per Cent Deformation, hr	Minimum Creep Rate, %/hr	Test Time, hr ^(b)	Elonga- tion, %
	Nom- inal Ti	Analysis							
		Ti ^(a)	C						
1800 F									
Ti2-4	6.3	4.5	0.23	Induction melted and cast in copper mold ^(c) ; rolled at 1500 F	500	0.5	2.0	5.8	36.8
Ti12	15.0	12.1	0.20	Arc melted; re- melted in BeO crucible; forged and rolled at 1700 F	"	0.5	0.19	120.	22.3
Ti100	100.0	99.6	0.38	Ditto	"	<0.1	25.	1.3	94.7

(a) Ti by difference except for Ti2-2 and Ti2-4 which were analyzed directly for Ti.

(b) Test discontinued before rupture except for Ti2-4 which was ruptured during test.

(c) Melted twice; inverted for second melting.

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TABLE A-3. CREEP DATA FOR URANIUM-ZIRCONIUM ALLOYS AT
1500 and 1800 F IN VACUUM

Alloy	Composition, wt %			Condition	Stress, psi	Time for 1 Per Cent Deformation, hr	Minimum Creep Rate, %/hr	Test Time, hr ^(b)	Elonga- tion, %
	Nom- inal Zr	Analysis							
		Zr ^(a)	C						
<u>1500 F</u>									
31	5.0	7.1	0.07	Induction melted and cast in graphite; rolled at 1550 F	500	0.8	0.65	6.0	8.1
26	11.3	12.6	0.08	Ditto	1422	< 0.1	43.	1.0	93.8
783-4	22.4	25.8	--	Arc melted twice; jacketed, forged, and rolled at 1450 F	500	0.45	1.0	11.	14.
784-5	46.5	47.1	--	Ditto	"	56.	0.013	169.	15.1
789-2	72.3	72.6	--	"	"	40.	0.021	162.7	12.3
<u>1800 F</u>									
Zr3-7	28.0	11.8	0.27	Induction melted and cast in copper mold; rolled at 1500 F	240	<0.1	~35.	0.2	7.0
783-5	22.4	25.8	--	Arc melted twice; jacketed, forged, and rolled at 1450 F	500	0.36	1.5	13.	29.5
784-6	46.5	47.1	--	Ditto	"	0.57	1.7	7.5	36.2
Zr4-7	53.5	63.7	0.75	Induction melted and cast in copper mold; rolled at 1500 F	"	0.5	2.0	21.	65.3
789-4	72.3	72.6	--	Arc melted twice; jacketed, forged, and rolled at 1450 F	"	0.16	5.5	1.8	37.

(a) Zr by difference except for Zr3-7 and Zr4-7.

(b) Test discontinued before rupture except for Zr3-7, which was ruptured during test.

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TABLE A-4. CREEP DATA FOR URANIUM-TANTALUM, URANIUM-COLUMBIUM, AND TWO TERNARY URANIUM ALLOYS AT 1500 and 1800 F IN VACUUM

Alloy	Composition, wt %							Condition	Test Temp, F	Stress, psi	Time for 1 Per Cent Deformation, hr	Minimum Creep Rate, %/hr	Test Time, hr ^(b)	Elonga- tion, %
	Nominal			Analysis										
	Ta ^(a)	Cb	Other	Ta	Cb	Other	C							
Ta1-4	7.8	--	--	5.8	--	--	0.09	Induction melted and cast in copper mold; rolled at 1500 F	1800	500	32.5	0.027	98.	8.1
Ta1-2	7.8	--	--	5.6	--	--	0.10	Ditto	1500	"	>162. (c)	0.0007	162. (c)	0.2 (c)
72	6.0	--	--	6.0	--	--	0.16	Multiple arc melted in water-cooled mold	1500	"	0.75	0.11	91.1	16.0
29	20.0	--	--	7.5	--	--	0.21	Induction melted and cast in graphite mold	1500	"	1.0	0.35	19.7	10.0
73	10.0	--	--	12.6	--	--	0.10	Multiple arc melted in water-cooled mold	1500	"	0.6	0.35	43.9	5.9
74	15.0	--	--	18.6	--	--	0.14	Ditto	1500	"	8.0	0.07	65.5	6.7
50	20.3	--	--	23.3	--	--	0.17	Induction melted and cast in graphite	1500	"	12.0	0.011	116.6	10.7
42	--	4.1	--	--	0.3	--	0.14	Induction melted and cast in graphite; rolled at 1500 F	1500	"	1.0	0.011	115.6	9.9
25	--	11.5	--	--	< 0.5	--	0.14	Induction melted in graphite; not rolled	1500	"	1.6	0.18	22.6	9.7
34	--	11.5	--	--	1.2	--	0.14	Induction melted and rolled at 1800 F	1500	"	7.0	0.02	160.	11.5
46	--	--	8Ta 50Zr	--	--	4.0Ta 53.5Zr	0.20	Induction melted and cast in graphite; rolled at 1500 F	1500	"	48.0	0.015	167.	3.6
47	--	--	25Ti 30Zr	--	--	26.0Ti 24.0Zr	0.79	Ditto	1500	"	38.0	0.0043	212.	1.4

(a) Tantalum by difference except for specimens Ta1-4, Ta1-2, 29, and 46.

(b) Tests discontinued before rupture except for Ta1-4, 50, 25, and 34, which were ruptured.

(c) Stress raised at 162 hours.

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TABLE A-5. CREEP DATA FOR MOLYBDENUM-URANIUM DIOXIDE COMPOSITES AT 1800 F IN VACUUM

Specimen	Nominal Wt % UO ₂	Condition	Stress, psi	Time for 1 Per Cent Deformation, hr	Minimum Creep Rate, %/hr	Time for Failure, hr	Elonga- tion, %
J138-2	10	Swaged at 3270 F in Mo jacket	2,500 ^(a)	--	0.0002	--	--
J138-4	10	Ditto	12,000	185	0.003	310. ^(b)	--
76	10	Sintered 2.5 hr at 3200 F and rolled at 2200 F in steel jacket	"	--	0.0004 ^(c)	289.	4.95
77	15	Ditto	"	--	0.0015	43.	(d)
81	20	Sintered 2.5 hr at 3200 F plus 2 hr at 3770 F	"	0.19	--	0.3	--

(a) Stress raised by increments to 20,000 psi.

(b) Test discontinued before failure.

(c) Between 210 and 277 hours in test the specimen exhibited this creep rate.

(d) No measurable deformation after rupture.

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FIGURE A-1. TIME-DEFORMATION CURVES FOR CAST URANIUM-MOLYBDENUM ALLOYS
AT 1500 F AND 500 PSI IN VACUUM
All tests were discontinued before rupture.

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FIGURE A-2. TIME-DEFORMATION CURVES FOR ROLLED URANIUM-MOLYBDENUM ALLOYS AT 1500 F AND 500 PSI IN VACUUM
All tests were discontinued before rupture.

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FIGURE A-3. TIME-DEFORMATION CURVES FOR URANIUM-MOLYBDENUM ALLOYS AT 1500 F AND VARIOUS STRESSES IN VACUUM

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FIGURE A-4. TIME-DEFORMATION CURVES FOR URANIUM-TITANIUM ALLOYS AT 1500 F AND 500 PSI IN VACUUM
All tests were discontinued before rupture.

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FIGURE A-5. TIME-DEFORMATION CURVES FOR URANIUM-TITANIUM ALLOYS AT 1800 F AND 500 PSI IN VACUUM

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FIGURE A-6. TIME-DEFORMATION CURVES FOR URANIUM-ZIRCONIUM ALLOYS AT 1500 F AND 500 PSI IN VACUUM
All tests were discontinued before rupture.

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FIGURE A-7. TIME-DEFORMATION CURVES FOR URANIUM-ZIRCONIUM ALLOYS AT 1800 F AND 500 PSI IN VACUUM
All tests were discontinued before rupture.

A-5965

FIGURE A-8. TIME-DEFORMATION CURVES FOR URANIUM-TANTALUM ALLOYS AT 1500F AND 500 PSI IN VACUUM

Tests were discontinued before rupture except where indicated.

A-5966

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FIGURE A-9. TIME-DEFORMATION CURVE FOR A URANIUM-TANTALUM ALLOY AT 1800 F AND 500 PSI IN VACUUM

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FIGURE A-10. TIME-DEFORMATION CURVES FOR URANIUM-COLUMBIUM ALLOYS AT 1500 F AND 500 PSI IN VACUUM

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FIGURE A-II. TIME-DEFORMATION CURVES FOR A ZIRCONIUM-TITANIUM-URANIUM AND A ZIRCONIUM-TANTALUM-URANIUM ALLOY AT 1500 F AND 500 PSI IN VACUUM

Tests were discontinued before rupture.

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FIGURE A-12. TIME-DEFORMATION CURVES FOR MOLYBDENUM- UO_2 COMPOSITE BODIES AT 1800 F IN VACUUM
All specimens ruptured except J-138-4.

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FIGURE A-10. TIME-DEFORMATION CURVES FOR URANIUM-COLUMBIUM ALLOYS AT 1500 F AND 500 PSI IN VACUUM

A-5968

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FIGURE A-II. TIME-DEFORMATION CURVES FOR A ZIRCONIUM-TITANIUM-URANIUM AND A ZIRCONIUM-TANTALUM-URANIUM ALLOY AT 1500 F AND 500 PSI IN VACUUM
Tests were discontinued before rupture.

A-5969

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