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**THE MECHANICAL PROPERTIES OF BETA-QUENCHED URANIUM
AT ELEVATED TEMPERATURES**

by

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THE MECHANICAL PROPERTIES OF BETA-QUENCHED URANIUM AT ELEVATED TEMPERATURES

Frederic R. Shober, Lyle L. Marsh, and George K. Manning

The creep strength and tensile properties were determined in vacuum for beta-quenched, derby uranium. The stresses to produce a secondary creep rate of 0.0001 per cent per hr at 100, 250, 400, and 500 C were 48,000, 35,500, 4,600, and 1,300 psi, respectively. Ultimate tensile strengths were 114,500, 35,100, 11,100, and 8,500 psi at temperatures of 28, 300, 500, and 700 C, respectively. The creep and tensile strengths decrease quite rapidly with increasing temperature in the temperature range 250 to 400 C.

INTRODUCTION

The objective of this study was to provide design engineers with elevated-temperature data on the mechanical properties, particularly creep strength, of beta-quenched uranium. Such data will aid in the analysis of material failures resulting from stress-induced time-dependent deformation.

TENSILE PROPERTIES AT 28, 300, 500, AND 700 C

Material and Test Equipment

The uranium was obtained _____ in the beta-quenched condition.

The as-received bars were approximately 1.5 in. in diameter.

Standard 0.505-in. tensile specimens were machined from the bars. The gage sections were ground and specimens were tested without any additional heat treatment. Only one specimen was tested at each test temperature because of the limited quantity of material.

Elongation was measured by means of SR-4-type strain gages bonded to the specimen gage section. An SR-4 strain-gage indicator was utilized to indicate elongation, which could be read accurately to ± 0.000005 in. Elongations greater than 1.5 per cent were not obtained because of limitations of the strain gages. Total elongations were measured on all specimens after testing. The crosshead speed for all tests was 0.01 in. per min, which corresponds to an approximate strain rate of 0.003 per min.

All specimens tested at elevated temperatures were tested in a specially designed vacuum tank, which contained a resistance-wire-wound furnace, the specimen, and an extensometer. The extensometer was the clip-gage type which measures the elongation of a specimen through a concentric rod-in-tube arrangement. Spring-type clips with strain gages mounted on both surfaces were so constructed that a considerably greater strain range could be obtained from the strain gages. The leads from the gages and the thermocouple leads were brought through the wall of the vacuum tank and attached to the appropriate indicating instruments. The pressure in the vacuum tank was brought to 5μ of mercury before heat was applied to the specimen. The specimen was brought to the test temperature slowly to allow it to degas and held 1 hr before testing. The temperature was held constant within ± 1.5 C during the test.

Results

The results from these tests are tabulated in Table 1 and are shown graphically in Figure 1. The tensile strength of alpha uranium decreases quite rapidly with increasing temperature in the range from 28 to 500 C. The tensile strengths at 500 and 700 C are quite similar; however, the elongation at 700 C has been reduced by a factor of 4 compared with the elongation obtained at 500 C. The similarity in strength and the decreased ductility can be attributed to the change in crystal structure. The alpha-to-beta transformation occurs at approximately 654 C, the temperature at

TABLE 1. TENSILE PROPERTIES^(a) OF BETA-QUENCHED
URANIUM AT 28, 300, 500, AND 700 C

Test Temperature, C	Offset Yield Strength, psi		Tensile Strength, psi	Total Elongation in 2 In., per cent
	0.1 Per Cent	0.2 Per Cent		
28	22,000	28,000	114,500	20.4
300	15,300	18,500	35,100	39.8
500	5,300	5,800	11,100	49.0
700	4,800	5,600	8,500	11.6

(a) Strain rate of 0.003 per min.

FIGURE 1. STRESS VERSUS STRAIN CURVES FOR BETA-QUENCHED URANIUM AT 28, 300, 500, AND 700 C

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which the structure changes from an orthorhombic to a complex tetragonal structure.

Hardness of uranium at elevated temperatures, Figure 2, indicates by another test method that the strengths at 500 and 700 C would be similar. The hardness of uranium has been increased nearly fivefold by the transformation process. Greater strength has been achieved by the transformation with a considerable loss in ductility.

CREEP PROPERTIES AT 100, 250, 400, AND 500 C

Materials and Test Equipment

The material used in creep tests at 100, 250, and 400 C was supplied by HAPO and was cast from unpickled derby uranium. The average composition of the uranium is tabulated below.

Composition, ppm				
<u>Carbon</u>	<u>Nitrogen</u>	<u>Iron</u>	<u>Silicon</u>	<u>Hydrogen</u>
393	56	37	30	1.98

The material was received as 1.5-in.-diameter bars and was subsequently forged at 577 C to 1.125-in.-square bars. The bars were forged from a helium-atmosphere furnace and water quenched after forging. The forged slugs were rolled to 0.50-in.-diameter rod from a salt bath at 577 C, and then air cooled. The slugs were reduced approximately 88 per cent in rolling. All rolled material was heat treated 1/2 hr at 725 C in a salt bath and water quenched. The rods were washed and pickled.

Prior to machining, samples were cut from each end and the center of the bars for room-temperature hardness and grain-size determination. These tests were made to check the uniformity obtained from the heat treatment and quench. The hardness values and grain sizes are shown in Table 2 and Figure 3, respectively. There were only very slight differences in hardness and in grain size, indicating no effective differences in properties from end to end in the as-quenched bars.

Tensile-creep specimens 3 in. long and with 2-in.-long 0.25-in.-diameter gage sections were machined from the heat-treated rods. The gage sections of all specimens were surface ground. Testing was done with no additional heat treatment.

FIGURE 2. HARDNESS OF URANIUM AT ELEVATED TEMPERATURES

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TABLE 2. HARDNESS OF BETA-QUENCHED
URANIUM RODS

Rod From Ingot No.	Portion of Rod	Average Hardness ^(a) , Rockwell A
M-4481	End	55.7
	Center	55.6
	End	55.4
M-5427	End	54.8
	Center	54.5
	End	54.0
M-5039	End	54.6
	Center	55.4
	End	54.2

(a) Average of five determinations.

100X

a. End

N18496

100X

b. Center

N18494

100X

c. End

N18495

FIGURE 3. MICROSTRUCTURE OF BETA-QUENCHED URANIUM FROM VARIOUS PORTIONS OF ROLLED ROD, INGOT 5039

Creep tests at elevated temperatures were conducted in a specially designed vacuum creep unit shown in Figure 4. Each unit is essentially a resistance-wire-wound furnace enclosed in a vacuum chamber. The furnace is surrounded by eight concentric stainless steel radiation shields spaced 0.25 in. apart. Stainless steel baffles placed at the top and bottom of the furnace also help prevent heat loss from the ends of the furnace.

The furnace, reflectors, and baffles are enclosed in the vacuum chamber, which has a bellows arrangement at top and bottom. Figure 5 is an assembly drawing of the components. The grips holding the specimen pass through these bellows and are attached to a fixed frame and a lever arm. The bellows permit deformation of a test specimen without disturbing the vacuum system. The vacuum chamber has small Vycor windows that are diametrically opposed and are aligned with openings in the baffles and furnace tube to provide a means of reading the extensometer attached to the specimen during testing.

The load to produce the desired tensile stress is applied through a 9:1 lever-arm ratio. Provisions are made to balance out any extraneous weight of the testing equipment and to compensate for the loss in load due to the effect of the evacuated bellows. The load was readjusted for tests in which the extension exceeded 2 per cent.

The extension of the specimens during testing was measured by an optical method. The movement of intersliding platinum strips attached to specimens was measured with an optical comparator. Readings were taken at 24-hr intervals, except at the beginning of a test or when the specimen was elongating rapidly. Readings were taken on this group of tests every 10 min for the first hour, and then hourly for the following 8 hr. The sensitivity of the optical comparator is 50μ in.

Test temperatures were held within $\pm 3/4$ C for tests at 500 C and within $\pm 1/2$ C for tests at 400, 250, and 100 C. A Foxboro controller in combination with an anticipator-type controller circuit maintained these test temperatures. Before a load was applied to a test specimen, the chamber was evacuated to 5μ of mercury pressure and held at test temperature for 1 hr.

The creep specimens tested at 500 C were prepared from the same material as were the tensile-test specimens and were "triple-dipped" beta quenched. However, one creep test was performed at 500 C and 4500 psi on a specimen of the same material as was used in creep testing at lower temperatures; the specimen was heated $1/2$ hr at 725 C in a salt bath and water quenched. Creep curves for these two beta-quenched materials are given in Figure 6. The results were only slightly different, but the shape of the early portions of the curve were more noticeably different. It was felt ultimately that there was not sufficient difference between the two to warrant testing of both materials at 500 C.

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FIGURE 4. VACUUM CREEP UNIT AND STAND USED FOR ELEVATED-TEMPERATURE TESTS ON BETA-QUENCHED URANIUM

FIGURE 5. ASSEMBLY DRAWING OF VACUUM CREEP FURNACE

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FIGURE 6. A COMPARISON OF CREEP PROPERTIES AT 4500 PSI AND 500 C OF URANIUM BETA QUENCHED BY DIFFERENT PROCEDURES

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Results

The creep properties of beta-quenched uranium are summarized in Table 3 and in Figures 7 through 18. The deformation versus time curves have been plotted on two time scales to provide a better comparison of data at the short times. The curves in Figure 17 were plotted to show the variance of minimum creep rate with stress at the test temperatures. The slopes of these curves change between 250 and 400 C. This change in slope is probably indicative of a change in the dominant creep mechanism.

The relationship between the creep stress and test temperature is more clearly shown in Figure 18. In this figure, the stress to produce some definite secondary creep rate is plotted versus temperature. The stress to produce a definite secondary creep rate begins to decrease more rapidly in the temperature range between 250 and 400 C. The inflection points in the curves reflect a change in the mechanism for creep that is, presumably, due to the onset of rapid recovery.

By using the relation $\sigma = f(\dot{\epsilon}_e \Delta H/RT)$ with which J. E. Dorn(1) and associates successfully correlated the creep of aluminum, iron, nickel, copper, zinc, platinum, gold, and lead at elevated temperatures, a value for ΔH of approximately 52,000 kcal per mole was calculated for temperatures in the range 400 to 500 C. In the above relationship σ = stress, $\dot{\epsilon}$ = secondary creep rate, R = gas constant, T = absolute temperature, and ΔH = the activation energy for creep. Dorn also found that for a given metal the ΔH value for creep agreed quite well with the activation energy for self-diffusion. A second correlation reported by Dorn was that there is a linear relationship between the melting temperature of a given metal and the activation energy for self-diffusion. Assuming this to be correct, such a plot predicts a melting temperature for uranium of approximately 1130 C which is very close to the accepted value of 1133 C(2). The calculated value for the activation energy of creep also agrees quite well with the value of 50,000 cal per mole for grain-boundary relaxation determined by internal friction methods reported by R. E. Maringer(3).

Microstructure

Representative microstructures of as-treated material are shown in Figure 3. This is a typical beta-quenched structure: large grains with smaller grains mixed throughout the structure. The larger grains have some twinned regions.

(1) References at end.

TABLE 3. CREEP PROPERTIES OF BETA-QUENCHED URANIUM AT 100, 250, 400, AND 500 C

Specimen	Test Temperature, C	Stress, psi	Elongation, per cent					Time at Test, hr	Time for Third-Stage Creep, hr	Minimum Creep Rate, per cent per hr	Time Interval for Secondary Creep Rate, hr
			Load On	100 Hr	500 Hr	1000 Hr	Total				
5039-2(a)	100	80,000	12.00	-	-	-	27.20	8	5	0.83	1-5
5039-3(a)	100	75,000	9.00	-	-	-	26.00	59	32	0.16	20-32
5039-4(a)	100	70,000	6.35	18.30	-	-	28.80	272	85	0.034	50-85
5039-5	100	60,000	3.30	7.40	8.80	9.35	9.36	1009	-	0.001	700-1009
5039-6	100	50,000	1.45	2.73	3.04	3.18	3.18	1010	-	0.00019	750-1010
4881-1	100	40,000	0.92	1.46	1.58	1.61	1.61	1008	-	0.00002	300-1000
4881-2(a)	250	50,000	Approx. 15.00	Ruptured on application of load			36.00	-	-	-	-
4881-3(a)	250	45,000	8.60	-	-	-	39.20	21 min	11 min	-	-
4881-4(a)	250	40,000	3.00	-	-	-	29.70	43.1	34	0.16	25-34
4881-12	250	37,500	2.30	10.40	12.90	14.50	14.50	1007	-	0.0022	800-1007
4881-11	250	35,000	0.95	1.93	2.67	3.14	3.14	1007	-	0.00048	800-1007
4881-5(a)	400	20,000 increased to 35,000	0.26	Ruptured on application of 35,000			41.30	-	-	-	-
4881-6(a)	400	30,000	3.98	-	-	-	38.40	4 min	-	-	-
4881-7(a)	400	28,400	4.08	-	-	-	32.40	9 min	-	-	-
4881-8(a)	400	23,000	0.90	-	-	-	30.70	2.5	1	2.50	0.5-1
4881-9(a)	400	15,000	0.52	8.80	-	-	31.20	132	25	0.043	10-25
4881-10	400	10,000	0.075	0.70	2.51	5.80	5.80	1000	-	0.0045	250-450
4881-13	400	8,000	0.065	0.35	1.15	-	1.92	848	-	0.0020	200-848
5039-1(a)	500	4,500	0.10	7.90	21.2	-	39.45	565	480	0.026	-
HS-5(a)	500	5,500	0.04	8.25	-	-	35.00	152	25	0.041	15-25
HS-4(a)	500	4,500	0.07	2.42	18.00	-	42.60	591	100	0.024	50-100
HS-7(a)	500	3,500	0.015	1.20	7.00	26.50	39.00	1134	150	0.009	50-150
HS-6	500	3,000	0.03	0.74	3.20	7.20	7.80	1077	-	0.0058	50-400
HS-2	500	2,500	0.02	0.43	1.30	2.22	4.25	2200	-	0.0019	1500-2200
HS-1	500	2,000	0.04	0.24	0.50	0.75	1.70	2300	-	0.0006	1000-2300

Note: Specimens rolled at 577 C, held 1/2 hr at 725 C, and water quenched, except where noted by Footnote (b).

(a) Ruptured during test.

(b) Rolled at 575 C, held 85 sec at 735 C and 30 to 40 sec at 595 C, water quenched.

FIGURE 7. DEFORMATION-TIME CURVES FOR BETA-QUENCHED URANIUM AT 80,000, 75,000, 70,000, 60,000, 50,000, AND 40,000 PSI AND 100 C

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FIGURE 8. DEFORMATION-TIME CURVES FOR BETA-QUENCHED URANIUM AT 80,000, 75,000, 70,000, 60,000, 50,000, AND 40,000 PSI AND 100 C

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FIGURE 9. DEFORMATION-TIME CURVES FOR BETA-QUENCHED URANIUM AT 45,000, 40,000, 37,500, AND 35,000 PSI AND 250 C

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FIGURE 10. DEFORMATION-TIME CURVES FOR BETA-QUENCHED URANIUM
AT 45,000, 40,000, 37,500, AND 35,000 PSI AND 250 C

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FIGURE II. DEFORMATION-TIME CURVES FOR BETA-QUENCHED URANIUM AT 23,000, 15,000, 10,000, AND 8000 PSI AND 400 C

FIGURE 12. DEFORMATION-TIME CURVE FOR BETA-QUENCHED URANIUM
AT 23,000 PSI AND 400 C

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FIGURE 13. DEFORMATION-TIME CURVES FOR BETA-QUENCHED URANIUM AT 23,000, 15,000, 10,000, AND 8000 PSI AND 400 C

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FIGURE 14. DEFORMATION-TIME CURVES FOR TRIPLE-DIPPED BETA-QUENCHED URANIUM AT 5500, 4500, 3500, 3000, 2500, 2000 PSI AND 500 C

FIGURE 15. DEFORMATION-TIME CURVES FOR HANFORD TRIPLE-DIPPED BETA-QUENCHED URANIUM AT 3000, 2500, AND 2000 PSI AND 500 C

A-15878

FIGURE 16. DEFORMATION-TIME CURVES FOR HANFORD TRIPLE-DIPPED BETA-QUENCHED URANIUM AT 5500, 4500, AND 3500 PSI AND 500 C

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FIGURE 17. RELATIONSHIP BETWEEN CREEP STRESS AND CREEP RATE AT 100, 250, 400, AND 500 C

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FIGURE 18. RELATIONSHIP BETWEEN CREEP STRESS AND TEMPERATURE FOR BETA-QUENCHED URANIUM IN THE TEMPERATURE RANGE 100 TO 500 C

A-15881

100X

N18497

FIGURE 19. MICROSTRUCTURE AFTER TESTING
AT 40,000 PSI AND 100 C

100X

N18499

FIGURE 20. MICROSTRUCTURE AFTER TESTING
AT 50,000 PSI AND 250 C

FIGURE 21. MICROSTRUCTURE AFTER TESTING
AT 10,000 PSI AND 400 C

FIGURE 22. MICROSTRUCTURE AFTER TESTING
AT 4500 PSI AND 500 C

Figures 19, 20, 21, and 22 are representative microstructures of uranium in the as-tested condition. The microstructures of the as-tested materials could be described as generally falling in the following categories:

- (1) Figure 19, moderately twinned structure
- (2) Figure 20, severely twinned structure
- (3) Figure 21, twin growth and grain-fragmented structure
- (4) Figure 22, grains breaking up to form small equiaxed grains.

There did not appear to be any correlation between microstructure and test temperature, total deformation or time at test.

REFERENCES

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- (2) The Reactor Handbook, Vol. 3, (April, 1953), "Materials", p 437.
SECRET
- (3) Maringer, R. E., Johnson, R. D., and Manning, G. K., "Dimensional Stability of Uranium", Proceedings of AEC Information Meeting, (April, 1955). SECRET

FRS:LLM:GKM/mm