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ELEVATED-TEMPERATURE MECHANICAL PROPERTIES OF
URANIUM WITH VARIOUS PROCESSING HISTORIES

By

L. G. Wexlin

AEC RESEARCH AND DEVELOPMENT REPORT

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TECHNICAL DIVISION
NATIONAL LEAD COMPANY OF OHIO

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ABSTRACT

Specimens for mechanical testing were prepared from standard production uranium in the cast, extruded, and rolled conditions. Some of the metal of each type was beta heat treated. The mechanical properties investigated were: tensile, tensile impact, drop hammer, hardness, and compression. The tests were conducted at temperatures ranging from 885 to 1235°F. A few tests were made at higher temperatures.

1. INTRODUCTION

Although many tons of uranium fuel cores have been produced for the AEC's production reactors by rolling or extruding in the high alpha temperature range, only limited information exists on the mechanical properties of uranium above 600°F. While significant improvements in rolling and extruding have been achieved, largely by empirical methods, information on the mechanical properties of uranium is needed for further improvement of the present fabrication processes and for the development of new processes. Some of the alternate processes being considered, or that have been considered, are rotary swaging, rotary piercing, rotary elongation, sink reduction, mechanical piercing, and extrusion.

The mechanical properties of uranium can be affected by (1) the fabrication processes: casting, rolling, or extruding, (2) the type of heat treatment, and (3) the direction of the applied stress with respect to the deformation that takes place during fabrication.

Therefore, test specimens having different fabrication and thermal histories were selected in the radial, tangential, and longitudinal directions. The tensile, tensile impact, drop hammer, hardness, and compression tests were performed off site by several industrial laboratories under sub-contract with the National Lead Company of Ohio. Test temperatures ranged from 885 to 1370°F.

2. SUMMARY OF RESULTS

1. As expected, the tensile, yield, and compressive strengths and the hardness of all specimens decreased as test temperatures increased, with the lowest values being recorded at temperatures just below the beta transformation. Conversely, elongation, reduction of area, and reduction of height increased as test temperatures increased and were highest just prior to beta transformation.

2. The mechanical properties of uranium were affected by the grain size. The reduction of area, hardness, and compressive strength were nearly the same in as-extruded and as-rolled specimens. However, the reduction of area and elongation were higher, and tensile strength, yield strength, compressive strength, and hardness were lower in the fine-grained as-rolled specimens than in the large-grained as-cast specimens.

The resistance to deformation (percent reduction of height) of the drop hammer specimens was not affected by either prior deformation or grain size. The surface appearance of impacted specimens was dependent on the prior grain size; the smaller the grain size the smoother was the surface.

3. Orientation created by extrusion or rolling was noticeable in the results of tests made in various specimen directions. Generally, mechanical properties were poorer in the tangential and radial directions than in the longitudinal direction. Crystallite orientation was randomized by beta-heat-treating the specimens prior to testing; this rendered the mechanical properties about the same in the three specimen directions.

4. Specimens tested in the beta phase were stronger in both tension and compression but considerably less ductile than those tested in the alpha phase.

5. Elongation was affected only slightly by increasing the testing strain rate (tensile vs tensile-impact tests). Reduction of area was decreased drastically by increasing the strain rate. The high-strain-rate tensile-impact test increased specimen temperatures enough that many specimens tested at high alpha temperatures were transformed into the beta phase.

3. SPECIMEN PREPARATION

Specimens for the mechanical property tests were prepared from ingots having the compositions shown in Table I and having the following processing histories:

Cast

Cast and beta heat treated*

Extruded** (4:1 reduction ratio) from a cast ingot

Extruded** (4:1 reduction ratio) from a cast ingot and beta heat treated

Rolled** (37:1 reduction ratio) from a cast ingot

Rolled** (37:1 reduction ratio) from a cast ingot and beta heat treated

* Heated to 1350°F in molten salt and quenched in water.

** Extruding and rolling were performed at about 1150°F.

TABLE I Chemical Composition (ppm)

Ingot	C	N	Al	B	Be	Bi	Cd	Cr	Cu	Fe	Mg	Mn	Mo	Ni	Pb	Si	Sn	V	Zn	H ₂	Density (g/cm ³)
<u>Cast</u>																					
1	331	33	13	<.15	<1	<1	<.2	10	2	79	<4	10	<6	26	<1	26	<1	<5	<20	—	18.99
2	266	68	12	<.15	<1	<1	<.2	12	3	76	<4	9	<6	41	<1	24	1	<5	<20	1.1	18.97
3	535	39	8	<.15	<1	<1	<.2	10	3	77	<4	11	<6	32	<1	29	<1	<5	<20	—	18.94
<u>Extruded</u>																					
4	363	24	9	<.15	<1	<1	<.2	9	3	78	<4	7	<6	21	<1	34	<1	<5	<20	—	—
5	245	61	18	<.15	<1	<1	<.2	23	10	99	<4	9	<6	37	4	34	<1	<5	<20	—	18.96
6	370	30	12	<.15	<1	<1	<.2	15	8	101	<4	9	<6	34	<1	33	<1	<5	<20	—	18.95
7	264	65	18	<.15	<1	<1	<.2	20	5	95	<4	8	<6	30	7	33	<1	<5	<20	—	18.95
8	343	24	13	<.15	<1	<1	<.2	13	6	98	<4	8	<6	31	<1	35	<1	<5	<20	1.5	18.97
9	284	41	14	<.15	<1	<1	<.2	8	4	75	<4	12	<1	34	4	25	<1	<5	<20	—	18.96
10	269	75	12	<.15	<1	<1	<.2	9	7	63	<4	8	<6	37	<1	27	<1	<5	<20	1.7	18.99
11	342	22	9	<.15	<1	<1	<.2	24	7	172	<4	10	<6	36	<1	32	<1	<5	<20	—	—
12	358	19	9	<.15	<1	<1	<.2	12	7	88	<4	10	<6	37	<1	30	<1	<5	<20	—	18.94
<u>Rolled</u>																					
13	640	80	<6	<.15	<1	<1	<.2	10	4	105	<4	10	<6	18	<1	36	2	<5	<20	0.6*	18.87
14	576	73	<6	<.15	<1	<1	<.2	10	4	100	<4	10	<6	24	<1	40	<1	<5	<20	1.7	18.89

* Analysis after beta heat treatment.

Specimens were obtained whenever possible from the cast ingots, extruded billets, and rolled rods in three directions: longitudinal, radial, and tangential. No tangential specimens were cut from the rolled rods because of the small rod diameter, and no radial specimens were cut from cast ingots or extruded billets for tensile or tensile-impact testing because of the specimen length required.

Figure 1 shows typical grain structures of specimens having the above six processing histories.

FIGURE 1 Typical Grain Structures of Test Specimens (3X)

4. EQUIPMENT AND TESTING PROCEDURE

The equipment and the testing organizations^{1,2,3} employed for the various tests are listed below:

- a. Tensile and compression tests were performed with a 120,000-pound-capacity Baldwin universal testing machine by the Southern Research Institute, Birmingham, Alabama.
- b. Tensile-impact tests were performed with a Sonntag universal impact machine by New England Materials Laboratory,* Medford, Massachusetts.
- c. Drop hammer tests were performed with the unit shown in Figure 2 by New England Materials Laboratory.*
- d. Hardness tests were performed with a standard floor model Wilson Rockwell test machine by New England Materials Laboratory.*

* Now Teledyne Materials Research Company.

FIGURE 2 Drop Hammer

Tensile, hardness, and compression specimens were heated and tested in an argon atmosphere. The specimens for the tensile - impact and drop hammer tests were heated in a neutral potassium-lithium chloride salt bath and then transferred to the testing unit.

Tests were performed on duplicate specimens at temperatures of 885, 955, 1025, 1095, 1165, and 1235°F except for the compression test which used 1150 and 1200°F, instead, for the two upper temperatures. Also, a few tests were run at 1250, 1300, 1305, and 1370°F.

The test temperature of 1235°F is slightly above the alpha-to-beta transformation of uranium; however the temperature control during testing was usually not accurate enough to insure that the specimens tested at 1235°F were in the beta phase. Hence the results at this temperature were unreliable. Because of this, test temperatures were changed to avoid the difficulty in the compression tests.

Detailed descriptions of the equipment and procedures may be found in the Appendix.

5. RESULTS AND DISCUSSION

Results of the various tests are described below, and the test data are tabulated in the Appendix. The data were subjected to a statistical analysis of variance to assist in the interpretation of the results. These calculations are not included in this report.

5.1 Tensile Tests

Results, shown in Figure 3, were as follows:

- a. The ultimate tensile strengths (longitudinal direction) of the rolled specimens (37:1 reduction ratio) were less, at all temperatures tested, than the tensile strengths of either the extruded specimens (4:1 reduction ratio) or the cast specimens. The tensile strengths of the extruded and cast specimens were similar. The 0.2% offset yield strengths (listed in the Appendix) were affected about the same as the ultimate tensile strengths. The yield strength values are considered less precise than the ultimate tensile strength and therefore are not shown in Figure 3.
- b. The smaller the grain size the larger was the elongation. Rolled specimens, which had the smallest grains, elongated the most. Differences in elongation between the rolled and the extruded or cast specimens increased rapidly with increasing temperatures in the alpha range (1235°F is in the beta range).
- c. The reduction of area was essentially the same for both the rolled and extruded specimens at all test temperatures. However, the reduction of area of cast specimens was less than that for the rolled and extruded specimens at the lower test temperatures.

It is believed that the tensile tests were performed at slow enough strain rates and at temperatures that allowed a creep, grain-boundary shear mechanism to predominate, as discussed by Reed-Hill, Conrad, and others.^{4,5} They have shown that polycrystalline materials undergo deformation at elevated temperatures by what is called grain-boundary shear but which is actually

FIGURE 3 Tensile Properties of Rolled, Extruded, and Cast Uranium (Rolled and Extruded Specimens Tested in the Longitudinal Direction)

plastic deformation at the boundary and not a simple sliding of one grain over another. Recovery, which appears as metal softening, occurs first in areas of high strain energy which are near the grain boundaries. This softening permits additional plastic deformation to occur near the grain boundaries. Thus, it would be expected that more plastic deformation (elongation) would occur with metals having a greater number of grain boundaries; i.e., more grains as indicated by a finer grain size. This is shown in Figure 3 where the fine-grained, rolled specimens had elongation values higher than those of the coarse-grained, cast specimens. Deformation strains from prior working and fine-grained structures are accepted as major contributors to changes in mechanical properties. However, higher temperatures tend to reduce strains in metal, and therefore, the predominant cause of the higher elongation values of the rolled specimens was the fine-grain structure.

In Figure 3, the elongation of both the cast and extruded specimens leveled off with test temperature, even though the tensile strength continued to drop. This was apparently the result of highly localized deformation at the fracture. This large amount of necking produced the high reduction-of-area values in specimens tested at the higher alpha-phase temperatures. Measuring the elongation over shorter gage lengths would have resulted in higher elongation values for these specimens.

Figure 3 also shows that the elongation of the rolled specimens increased as the test temperature increased, even though the reduction of area was fairly constant and nearly identical to those of the cast and extruded specimens. It was difficult to measure specimens that had extreme reductions of area. These values were plotted as 95% although some were higher.

Figure 4 shows that rolled, beta-heat-treated specimens had higher tensile strengths and lower ductilities than the as-rolled specimens. The beta-heat-treated specimens also had considerably larger grain sizes than the as-rolled specimens (see Figure 1). These data support the thesis set forth above that elevated temperature deformations are determined to a considerable degree by grain size.

The tensile strength, elongation, and reduction of area of the cast, beta-heat-treated and extruded, beta-heat-treated specimens were similar to the corresponding values of the rolled, beta-heat-treated specimens shown in Figure 4 and, hence, are not plotted. However, the photomicrographs in Figure 1 show that both the cast, beta-heat-treated and extruded, beta-heat-treated grains are larger than the rolled, beta-heat-treated grains. This indicates that the mechanical properties of uranium are affected by factors other than grain size, particularly large hot deformations.

The tensile strength, yield strength, and elongation of extruded uranium are slightly lower in the tangential direction (90 degrees to the extrusion direction) than in the longitudinal direction (parallel to the extrusion direction). These relationships can be seen in Figure 5, except that yield strength values are not shown. They were similar to the tensile strength values but slightly lower. There were no differences in reduction of area with specimen direction. Directional response is caused by crystallite orientation, which is sometimes called "crystallographic fibering," and by what is called "mechanical fibering."⁶ Mechanical fibering in polycrystalline metals may arise from elongated inclusions, blowholes, cavities, segregation, nonmetallic inclusions, layers of small grains, or the elongated shapes of the grains themselves.

FIGURE 4 Effect of Beta Heat Treatment on the Tensile Properties of Rolled Uranium (Longitudinal Direction)

FIGURE 5 Effect of Specimen Direction on the Tensile Properties of Extruded Uranium

5.2 Tensile-Impact Tests

Rolled specimens, which had the greatest amount of prior deformation (and the smallest grain size), had the most resistance to fracture, as shown in Figure 6. Rolled specimens also had higher values for elongation and reduction of area than the extruded or cast specimens, as shown in Figure 7. The extremely fine grains in the rolled specimens probably were responsible for the greater ductility.

Tensile-impact tests showed the effects of specimen direction better than the tensile tests (compare Figures 5 and 8). In the tensile tests, the reduction-of-area values were practically the same in both the tangential and longitudinal directions; however, the tensile-impact test showed that the reduction-of-areas values in the longitudinal direction were greater at all temperatures than the values in the tangential direction.

The effect of beta heat treatment on the elongation and reduction of area of rolled rods as measured by tensile-impact tests are shown in Figure 9. Note the similarity to the tensile tests shown in Figure 4. However, the effects of beta heat treatment on the energy required to break the specimens were quite different. The tensile tests showed that the strength of the rolled beta-heat treated rods was higher than the as-rolled rods at all temperatures tested, but the tensile-impact tests indicated that the energy required to fracture the rolled beta-heat treated specimens was less than for the as-rolled rods.

The difference in energy required to fracture the rolled specimens as compared with the rolled, beta-heat treated specimens could have been due to the faster strain rate of the tensile-impact

FIGURE 6 Tensile-Impact Properties of Rolled, Extruded, and Cast Uranium (Longitudinal Direction)

FIGURE 7 Reduction of Area and Elongation of Rolled, Extruded, and Cast Uranium from Tensile-Impact Test. (Longitudinal Direction)

FIGURE 8 Effect of Specimen Direction on Tensile-Impact Properties of Extruded Uranium

FIGURE 9 Effect of Beta Heat-Treatment on the Tensile-Impact Properties of Rolled Uranium in the Longitudinal Direction

tests. This may have reduced the effectiveness of creep from grain-boundary shear as a deformation mode, and the dislocation-slip mechanism may have contributed more to the deformation. The grain shape could not be changed as much in the absence of creep and its accompanying greater plasticity.

The macrostructures of the shanks of the extruded tensile-impact specimens are shown in Figure 10. The structures do not appear much different from the structures prior to machining shown in Figure 1, except for the specimen tested at 1235°F, hence it was concluded that heating prior to testing had no effect. All specimens were similarly examined.

To protect tensile-impact specimens from oxidation, they were heated in molten salt (potassium and lithium chlorides). A film of molten salt adhered to the specimens as they were transferred to the tensile-impact unit. Hanks, Taub, and Doll⁷ reported that uranium picked up hydrogen when heated to high alpha temperatures in a salt bath and stated that this resulted in a loss of ductility.

EXTRUDED

FIGURE 10 Structures of Fractured Tensile-Impact Specimens (3X)

Hydrogen analyses of specimens which were tested at 885 and 1235°F are shown in Table II. It can be seen that the total hydrogen content of the specimens did not increase significantly during the short exposure time (heating plus 10-minute soak time) in the salt bath. Surface hydrogen did not significantly increase in heating to 885°F but nearly doubled in heating to 1235°F.

TABLE II Hydrogen Content of Tensile-Impact Specimens

Process Used	Ingot H ₂ (ppm)	Tensile - Impact Specimens			
		Total H ₂ (ppm)		Surface H ₂ (ppm)	
		885°F	1235°F	885°F	1235°F
Cast	1.5	1.8	2.7	2.0	3.4
Cast and Beta Heat Treated	1.1	1.2	1.0	1.4	3.4
Extruded	1.5	2.4	1.8	2.2	3.2
Extruded and Beta Heat Treated	1.7	1.6	1.5	1.5	2.5
Rolled	1.7	1.3	1.5	1.4	4.0
Rolled and Beta Heat Treated	0.6	0.6	1.0	1.2	2.3

5.3 Drop Hammer Tests

Specimen deformation was measured by the percent reduction of height. The specimen surfaces were not deliberately lubricated before impact; however, the molten salt adhering to the specimens served as a rather poor lubricant. This was evidenced by the barreling of the specimens during impact.

Temperature had the greatest effect on the reduction of height. The higher the temperature the greater was the deformation, as shown in Figure 11. The only other variable that showed a possible effect on the resistance to deformation was the specimen direction; its effect is shown in Figure 12. Longitudinal specimens were more ductile than radial specimens at all test temperatures, except at 885°F where the ductility was about equal.

FIGURE 11 Effect of Temperature on Resistance to Deformation of Uranium by Drop Hammer

FIGURE 12 Effect of Specimen Direction on Resistance to Deformation of Rolled Uranium

A few anomalous values were obtained in reduction of height for the drop hammer specimens tested at 1165 and 1235°F. It is believed that the high strain rate of the test generated enough heat within the specimen to transform a portion into the beta phase.

Impacted drop hammer specimens are shown in Figure 13. These are typical of all specimens impacted at each test temperature. The amount of deformation of specimens in the beta phase (1305°F) was considerably less than the deformation of those in the alpha phase. However, the resistance to deformation at 1305°F was not much greater than the resistance to deformation of specimens impacted at the lowest alpha phase temperature (885°F). It is believed that the specimens in the beta phase had more resistance to deformation than was actually measured. It can be seen that the specimens tested at 1305°F mushroomed on impact. The relatively cold drop hammer anvil produced a thermal gradient within the specimen; hence the bottom end of the specimen was probably in the alpha phase and flowed more easily. The remainder of the specimen, in the beta phase, was considerably stiffer. Several attempts to impact specimens at higher beta phase temperatures produced similar results. The problem could probably be solved by use of a heated anvil.

One observation, not easily shown in photographs, was the effect of grain size on the external appearance of the impacted specimens. The surfaces of the impacted cast, extruded, and rolled specimens were rough, medium, and smooth, respectively.

5.4 Hardness Tests

The hardness of uranium is highly influenced by processing history. Figure 14 shows that the softer specimens are associated with the finer grain size produced in the heavily worked rolled metal. Figure 15 shows that the coarser-grained, rolled and beta heat treated specimens are

FIGURE 13 Typical Impacted Drop Hammer Specimens

harder than the finer-grained, as-rolled specimens. Note also (Figures 14 and 15) that the coarser-grained specimens do not soften with temperature as much as the finer-grained specimens.

A comparison of the hardness curves in Figures 14 and 15 shows that the rolled-beta-heat treated specimens are harder than the cast specimens having the larger grain size (see Figure 1).

The largest effect of specimen direction was exhibited by the extruded metal as shown in Figure 16. The extruded specimens had a large percentage of elongated grains.

Specimens tested in the beta phase (1235°F) were considerably harder than those tested in the high alpha phase.

5.5 Compression Tests

The large-grained cast specimens had higher compressive strengths (50% strain) than those of the fine-grained rolled specimens (see Figure 17). The yield strengths (0.2% strain) were essentially independent of grain size. The yield strength of specimens after beta heat treatment (Figure 18) was considerably higher than those of either the rolled or cast specimens. The compressive strengths of the beta-heat-treated specimens were about the same as those of the cast specimens regardless of the difference in grain size.

The small differences in compressive strength with specimen direction are shown in Figure 19. Yield strength was essentially unaffected by specimen direction.

FIGURE 14 Hardness of Cast and Rolled Uranium

FIGURE 15 Effect of Beta Heat Treatment on Hardness of Rolled Uranium

FIGURE 16 Hardness of Extruded Uranium in the Longitudinal and Radial Directions

FIGURE 17 Effect of Grain Size on Compressive Strength of Uranium

FIGURE 18 Effect of Beta Heat Treatment on Compressive Strength of Rolled Uranium Specimens (Longitudinal Direction)

FIGURE 19 Effect of Specimen Direction on Compressive Strength of Uranium Specimens

The yield and compressive strengths of all the beta-heat-treated specimens were the same regardless of the prior history of the metal, indicating that the beta heat treatment erased the effects of prior processing.

Fine-grained uranium in compression (as in tension) was found to be generally weaker than coarse-grained metal. Thus it is believed that grain-boundary shear predominates as the deformation mode in uranium slowly compressed at elevated temperatures.

6. CONCLUSIONS

These mechanical property tests at elevated temperatures showed that uranium with a fine-grained structure was not as hard nor as strong but was more ductile than uranium with a large-grained structure. Also, these properties were lower in the longitudinal direction than in either the radial or tangential directions because of orientation imparted by rolling and extrusion. The effects of prior processing on the mechanical properties decreased as test temperatures increased.

The effects of grain size or structure on mechanical properties was eliminated by beta heat treatment. This treatment resulted in metal with nearly uniform grain size and without directionality no matter how the metal had been processed prior to heat treatment.

The merits of each type of test discussed in this report are as follows:

- a. The test which best demonstrated the effects of processing methods and directionality was the tensile-impact test. The high strain rate of this test prevented creep deformation.
- b. The hardness test was somewhat less discriminating than the tensile-impact test, but specimen preparation was less costly. However, hardness was quite sensitive to specimen direction and moderately sensitive to specimen processing history and grain size.
- c. Tensile test results should be made more useful by increasing the strain rate. The extremely slow rate used during the tests (0.005 in./in./min) allowed some creep to affect the measurements. As a result, the tensile tests indicated only moderate differences in the effects of processing history and specimen direction, and these differences became less as the alpha test temperatures increased.
- d. The compression and drop hammer tests appear to be the least useful. However, because the resistance to deformation is temperature sensitive, the drop hammer test might serve as an economical and rapid method of estimating metal behavior during extruding and rolling.

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8. APPENDIX

8.1 Tensile Tests

8.1.1 Description of Equipment

Elevated-temperature tensile tests were performed by Southern Research Institute, Birmingham, Alabama, with a 120,000-pound-capacity Baldwin universal testing machine. The machine had been calibrated to have a loading accuracy of $\pm 0.5\%$ at all load levels.

An atmosphere of argon prevented oxidation of the tensile specimen during the test. The argon was contained by a stainless steel protection tube which surrounded the tensile specimen, as shown in Figure 20. The specimens were heated in the testing position by a resistance-element tubular furnace mounted on the tensile machine. Temperature was controlled by a potentiometer-controller and a chromel-alumel thermocouple positioned within the furnace chamber but outside the stainless steel protection tube (see Figure 20). Specimen temperatures were recorded on a strip-chart recorder from a chromel-alumel thermocouple wired directly to the specimen surface at the middle of the gage length.

FIGURE 20 Tensile Specimen, Protection Tube, and Thermocouple Arrangement Within Furnace

Elongation was measured by the strain gage extensometer attached to the crosshead of the machine in a manner that eliminated any extraneous movements. The elongation was recorded against load, as measured by the load weighing system of the machine, on an autographic recorder. A standard tensile test specimen (ASTM E8-61T) having a 2-inch gage length was used.⁸

8.1.2 Test Procedures

Heating rate and thermal gradient tests were made with a special specimen having an axial thermocouple at the center of the gage length at each of the six test temperatures prior to the actual tensile tests. Wired-on thermocouples were used for temperature control during the actual tensile testing.

The data from the above tests were used to determine the time required to heat a specimen to temperature. Five minutes soaking time was added to each heating period to insure thermal equilibrium.

To perform the tensile test, the specimen was placed in a protection tube, and the assembly was put into the furnace. The tube assembly was then purged with argon and heated to the preselected test temperature. After the soak period at the preselected temperature, the tensile test was performed using a constant strain rate of 0.005 in./in./min to rupture. The 0.2% offset yield strength and the ultimate tensile strength were determined from the recorded load-elongation curves. The elongation and the reduction of area were determined from measurements of broken tensile specimens. Duplicate tensile specimens were pulled at each of the six temperatures for each type of uranium and specimen direction. An extra specimen was tested when the tensile strengths of the duplicate tests differed by more than 10% or when significant differences in ductility occurred. The tensile data are listed in Table III.

8.2 Tensile-Impact Tests

8.2.1 Description of Equipment

The tensile-impact tests were performed by New England Materials Laboratory, Medford, Massachusetts, on a Sonntag universal impact machine equipped with a tensile-impact specimen holding fixture (Figure 21). The specimens were heated in a neutral potassium-lithium chloride salt bath in a resistance-element furnace. The temperature was controlled by a thermocouple immersed in the salt bath. An undersized tensile specimen with an elongated shank was used, as shown in Figure 21.

8.2.2 Testing Procedure

A time-temperature calibration curve was made prior to testing at each test temperature to establish the temperature drop in the specimen during the transfer from the salt bath to the holding fixture and impact. To obtain data for the calibration curves, a platinum, platinum-10% rhodium thermocouple was peened into a $\frac{1}{8}$ -inch-deep hole in the gage section of the specimen, and temperatures were recorded on a high-speed strip-chart recorder. The salt bath temperatures were then maintained at levels such that the specimens were at the required test temperature in the holding fixture after transfer. A constant transfer time of 4 seconds was maintained at all test temperatures.

FIGURE 21 Tensile-Impact Specimen, Holding Fixture, and Striker Block

Broken specimens were quenched in water after the tests. The energy absorbed by the impact was recorded, and the broken specimens were measured to obtain the percentage elongation (in 1 -inch gage length) and the percentage reduction of area at the point of fracture.

The broken test specimens were partially sectioned longitudinally so that the grain structure could be examined and photographed. The tensile impact data are listed in Table IV.

8.3 Drop Hammer Tests

8.3.1 Description of Equipment

Drop hammer tests were performed by the New England Materials Laboratory, Medford, Massachusetts. The drop hammer (Figure 2) consisted of a lower platen with two upright guide posts, an upper platen which was capable of moving vertically along the guide posts and which was held near the top of the posts by a magnet, and a large block of concrete that served as a base and absorbed the force of the impact. The upper platen, weighing 50 pounds, was released and dropped in a free fall of 4 feet.

The specimens were heated in a neutral potassium-lithium chloride salt bath in a resistance-element pot furnace. The temperature of the bath was controlled by an immersed chromel-alumel thermocouple. The specimen used was a cylinder $\frac{1}{2}$ inch in diameter and $\frac{3}{4}$ inch high.

TABLE III Tensile Properties of Uranium at Elevated Temperatures*

Process Used	Temperature (°F)													
	885		955		1025		1095		1165		1235		1370	
	Specimen Direction, Longitudinal (L) or Tangential (T)													
	L	T	L	T	L	T	L	T	L	T	L	T	L	T
<u>Cast</u>														
Ultimate Tensile Strength (psi)	13,600	14,300	10,400	9,600	7,100	7,600	5,900	6,000	4,000	4,400	3,200	3,700	—	5,600**
Elongation (in 2 in., %)	28.5	44.0	40.8	44.0	41.8	37.0	40.3	33.0	37.3	55.0	36.3	25.0	—	18.0**
Yield Strength (psi)	11,500	12,200	9,200	8,200	6,300	7,000	5,600	5,300	3,600	4,200	3,100	3,400	—	4,900**
Reduction in Area (%)	75.9	76.8	79.3	95.0	92.4	95.0	95.0	95.0	95.0	95.0	93.1	>95.0	—	33.8**
<u>Cast and Beta Heat Treated</u>														
Ultimate Tensile Strength (psi)	15,900	15,800	10,500	9,800	8,200	9,000	5,500	6,500	4,900	5,000	4,300	3,800	—	—
Elongation (in 2 in., %)	34.5	40.0	42.5	36.0	38.0	45.5	37.5	40.5	44.7	48.8	51.5	49.2	—	—
Yield Strength (psi)	14,300	14,800	10,100	9,200	8,000	8,500	5,000	6,200	4,400	4,600	4,000	3,600	—	—
Reduction in Area (%)	89.5	77.5	93.0	83.8	84.7	89.9	89.5	92.8	95.0	93.9	>92.0	>95.0	—	—
<u>Extruded</u>														
Ultimate Tensile Strength (psi)	13,200	13,300	10,600	8,600	8,600	7,000	6,700	5,100	4,800	3,600	3,700	3,100	—	6,300
Elongation (in 2 in., %)	48.5	45.5	55.8	38.8	55.7	52.8	51.3	54.5	50.2	44.0	34.0	37.0	—	42.0
Yield Strength (psi)	11,400	10,200	10,000	8,000	8,200	6,000	6,200	4,700	4,700	3,200	3,400	2,900	—	5,900
Reduction in Area (%)	81.5	79.8	92.6	88.1	93.7	95.0	93.7	95.0	95.0	95.0	90.2	>94.4	—	49.7
<u>Extruded and Beta Heat Treated</u>														
Ultimate Tensile Strength (psi)	16,000	14,500	12,400	10,800	9,200	8,400	7,300	6,400	5,100	4,700	3,800	3,600	—	6,000
Elongation (in 2 in., %)	38.3	41.5	41.8	45.2	45.0	44.5	50.3	44.0	51.0	45.2	37.0	41.5	—	34.5
Yield Strength (psi)	15,200	13,100	11,800	10,000	8,800	7,900	6,600	6,200	4,700	4,500	3,500	3,300	—	5,800
Reduction in Area (%)	73.4	75.3	84.0	83.0	92.0	87.6	93.5	91.9	95.0	94.5	95.0	92.7	—	43.8
<u>Rolled</u>														
Ultimate Tensile Strength (psi)	12,200	—	7,500	—	6,400	—	4,600	—	3,600	—	2,900	—	6,800**	—
Elongation (in 2 in., %)	57.3	—	68.5	—	77.8	—	89.2	—	96.0	—	50.5	—	54.0**	—
Yield Strength (psi)	8,900	—	5,500	—	5,200	—	3,800	—	3,000	—	2,400	—	6,500**	—
Reduction in Area (%)	82.9	—	91.0	—	93.0	—	94.4	—	95.0	—	94.8	—	~ 63**	—
<u>Rolled and Beta Heat Treated</u>														
Ultimate Tensile Strength (psi)	15,400	—	12,000	—	9,000	—	7,200	—	5,000	—	3,800	—	6,200	—
Elongation (in 2 in., %)	38.5	—	45.8	—	53.5	—	51.0	—	51.7	—	37.2	—	35.0	—
Yield Strength (psi)	14,500	—	11,300	—	8,400	—	7,000	—	4,600	—	3,500	—	5,700	—
Reduction in Area (%)	75.7	—	77.4	—	85.2	—	91.3	—	94.1	—	91.5	—	50.8	—

* All values are averages of two specimens unless otherwise noted.

** One specimen only.

TABLE IV Tensile-Impact Properties of Uranium at Elevated Temperatures*

Process Used	Temperature (°F)													
	885		955		1025		1095		1165		1235		1305	
	Specimen Direction, Longitudinal (L) or Tangential (T)													
	L	T	L	T	L	T	L	T	L	T	L	T	L	T
<u>Cast</u>														
Impact Energy (ft-lbs)	33.1	25.2	26.6	31.3	37.8	35.2	33.0	33.1	28.6	31.4	18.4	18.5	17.5**	15.0**
Elongation (in 1 in., %)	34.1	24.7	37.4	31.2	42.2	35.3	41.4	43.5	36.9	48.9	7.0	6.2	†	2.0**
Reduction in Area (%)	68.0	70.2	58.6	59.8	68.4	58.5	56.2	58.7	56.8	61.6	8.7	5.0	†	0.0**
<u>Cast and Beta Heat Treated</u>														
Impact Energy (ft-lbs)	45.6	45.3	35.3	36.5	42.0	36.8	38.0	30.1	42.7	38.2	21.7	23.6	29.0**	23.0**
Elongation (in 1 in., %)	35.8	36.0	32.6	35.0	43.4	38.3	43.2	33.0	49.2	62.3	13.1	14.5	3.7**	4.3**
Reduction in Area (%)	49.7	52.9	57.5	52.3	58.8	48.8	61.7	56.6	56.7	62.7	23.0	24.3	2.3**	0.0**
<u>Extruded</u>														
Impact Energy (ft-lbs)	51.3	45.0	50.1	40.6	50.8	43.7	48.7	40.9	41.1	33.5	20.5	20.0	27.5**	26.5**
Elongation (in 1 in., %)	45.9	34.9	52.5	35.4	62.7	36.9	64.3	45.4	58.5	45.5	9.9	11.5	3.3**	3.1**
Reduction in Area (%)	63.0	56.8	69.2	49.3	74.8	50.3	67.6	51.5	66.3	52.9	17.7	8.1	1.6**	0.0**
<u>Extruded and Beta Heat Treated</u>														
Impact Energy (ft-lbs)	50.9	49.0	44.2	45.7	41.1	43.7	47.5	43.1	41.7	36.7	18.0	19.4	29.0**	25.0**
Elongation (in 1 in., %)	47.1	39.8	44.8	45.8	44.5	39.4	61.2	52.1	58.7	44.5	6.6	8.4	3.6**	4.1**
Reduction in Area	49.5	46.8	61.9	59.5	62.0	54.8	67.7	59.9	71.0	61.2	1.2	25.1	4.0**	0.0**
<u>Rolled</u>														
Impact Energy (ft-lbs)	53.9	—	57.0	—	75.5**	—	55.5**	—	55.0**	—	21.5**	—	48.6**	—
Elongation (in 1 in., %)	41.3	—	63.0	—	62.6	—	69.0**	—	77.9**	—	2.8**	—	8.2**	—
Reduction in Area (%)	66.6	—	75.2	—	72.9	—	73.0**	—	74.9**	—	0.0**	—	9.4**	—
<u>Rolled and Beta Heat Treated</u>														
Impact Energy (ft-lbs)	53.6	—	49.0	—	51.0	—	47.4	—	41.0	—	20.5	—	44.0**	—
Elongation (in 1 in., %)	40.2	—	46.7	—	†	—	53.3	—	51.3	—	8.4	—	7.7**	—
Reduction in Area (%)	55.7	—	58.5	—	†	—	64.0	—	63.6	—	13.1	—	5.7**	—

* All values are averages of two specimens unless otherwise noted.

** One specimen only.

† Not calculated.

8.3.2 Test Procedure

The information obtained from the temperature calibrations made for the tensile-impact test was used also in the drop hammer tests. The procedure established was to heat the specimen in the salt bath to the desired temperature and allow the specimen to soak for 10 minutes. The specimen was then removed and placed on the anvil and impacted within a 4-second interval. The specimen was quenched in water immediately after impact. The reduction in height of the specimen was measured, and a notation of its appearance was made. The drop hammer data are listed in Table V.

8.4 Hardness Tests

8.4.1 Description of Equipment

Hardness tests were performed by the New England Materials Laboratory, Medford, Massachusetts, using a standard, floor model, Wilson Rockwell test machine. A cylindrical resistance furnace was mounted so as to surround an extended-length penetrator holder, a carbide ball penetrator, and a ceramic-capped lower anvil. Figure 22 shows the arrangement of penetrator, anvil, and thermocouples within the furnace. The furnace was clamped to a vertical column placed to one side of the working area. A water-cooled bottom plate with attached anvil rested on the standard table anvil mounted on the retractable screw of the machine. Specimens were inserted and removed by lowering the table and exposing the ceramic-capped anvil, then elevating the assembly to position the specimen within the furnace. Hardness readings were made within the furnace heating zone at the various test temperatures. Several hardness indentations were made on each specimen by moving the anvil and furnace with an indexing fixture incorporated as part of the vertical furnace support column.

The furnace temperature was measured and controlled by a chromel-alumel thermocouple extending upwards adjacent to the lower anvil with the tip positioned level with the top of specimen as shown in Figure 22.

The entire hardness tester with its furnace was enclosed in a glove box filled with argon.

The top of the tester containing the knife-edges of the mechanism was water-cooled to insure trouble-free operation. The specimen used was a cylinder about $1\frac{1}{4}$ inches in diameter and about $\frac{3}{8}$ inch high.

8.4.2 Testing Procedures

Temperature calibrations were made at each test temperature prior to testing by comparing control thermocouple temperature measurements with those obtained from a platinum, platinum-10% rhodium thermocouple peened into a $\frac{1}{8}$ -inch hole drilled into the surface of a specimen. This calibration corrected for possible errors induced in the control thermocouple by the argon gas flowing into the furnace chamber through the same inlet hole, as shown in Figure 23.

The specimen was placed in the furnace, heated to the test temperature, and held at temperature for 10 minutes. Readings were made using the Rockwell H scale ($\frac{1}{8}$ -inch diameter ball and 60

TABLE V Drop Hammer Properties of Uranium at Elevated Temperatures – Reduction of Height (%)*

Process Used	Temperature (°F)																				
	885			955			1025			1095			1165			1235			1305		
	Specimen Direction, Longitudinal (L), Tangential (T), or Radial (R)																				
	L	T	R	L	T	R	L	T	R	L	T	R	L	T	R	L	T	R	L	T	R
Cast	20.1	21.0	25.7	24.0	23.5	28.3	31.6	33.4	33.4	34.8	35.0	36.3	36.9	29.4	32.4	33.7	41.2	21.7	18.6**	14.0**	17.5**
Cast and Beta Heat Treated	22.4	21.6	18.8	19.4	22.3	18.4	30.4	29.5	27.4	31.2	31.9	32.0	32.2	30.3	33.1	35.5	35.3	33.5	22.0**	16.0**	7.8**
Extruded	21.3	16.1	18.3	24.3	16.9	19.9	32.1	26.2	18.1	31.9	30.6	32.4	35.2	29.0	32.5	39.5	34.1	32.8	16.4**	15.9**	13.1**
Extruded and Beta Heat Treated	15.4	18.9	19.6	26.5	25.1	24.3	28.2	29.7	26.7	31.0	30.6	28.1	29.5	33.2	30.6	33.5	36.0	29.7	16.2**	19.7**	16.0**
Rolled	17.5	—	18.2	27.5	—	16.3	29.1	—	25.0	34.0	—	27.1	34.3	—	30.5	36.0	—	31.7	19.0**	—	8.0**
Rolled and Beta Heat Treated	20.2	—	19.9	25.6	—	23.5	29.1	—	26.2	28.8	—	29.5	32.5	—	28.9	34.2	—	29.8	17.9**	—	8.0**

* All values are averages of two specimens unless otherwise noted.

** One specimen only.

TABLE VI Hardness of Uranium at Elevated Temperatures – Rockwell H*

Process Used	Temperature (°F)																				
	885			955			1025			1095			1165			1235			1300		
	Specimen Direction, Longitudinal (L), Tangential (T), or Radial (R)																				
	L	T	R	L	T	R	L	T	R	L	T	R	L	T	R	L	T	R	L	T	R
Cast	78.1	80.4	83.9	79.5	77.5	78.0	59.6	54.5	62.0	30.3	43.1	42.0	27.0	23.7	28.2	65.9	77.4	73.4	—	97.0**	80.6**
Cast and Beta Heat Treated	85.2	84.2	87.4	83.5	84.7	84.3	62.1	60.2	59.0	44.2	40.3	44.6	36.8	39.5	29.7	85.8	85.4	—	—	71.0**	69.3**
Extruded	73.6	88.4	79.9	71.0	81.2**	86.4	40.6	66.9	57.3	18.2	46.3	42.8	—	35.0	41.2	66.9	60.8**	67.1**	72.9**	88.3**	90.5
Extruded and Beta Heat Treated	91.0	87.4	91.8	86.9	84.3	88.9	69.0	57.7	73.4	48.0	43.4	48.0	39.2	29.0	39.6	74.2**	71.3	77.3	89.2**	76.6**	88.6
Rolled	72.1	—	79.1	69.4	—	71.6	39.8	—	43.6	11.8	—	21.1	—	—	7.1	73.0	—	83.8	65.9**	—	71.1
Rolled and Beta Heat Treated	89.3	—	89.9	85.9	—	85.3	58.0	—	59.2	44.1	—	43.1	37.3	—	25.3	81.5	—	78.6	68.8**	—	68.3

* All values are averages of two specimens and three impressions per specimen, unless otherwise noted.

** One specimen only.

kg load) and a penetration dwell time of 4.5 seconds. Four readings were taken on each test specimen at each test temperature. The first impression made was to seat the specimen properly; the other three impressions were recorded and averaged. Duplicate specimens were tested. The hardness data are listed in Table VI.

8.5 Compression Tests

8.5.1 Description of Equipment

The elevated-temperature compression tests were performed by Southern Research Institute, Birmingham, Alabama, using a 120,000-pound-capacity Baldwin universal testing machine. The machine was calibrated to a loading accuracy of $\pm 0.5\%$ at all load levels. A compression subpress and a split tube furnace arranged to contain an argon atmosphere were used for the tests.

The subpress is illustrated in Figure 23. The design conformed to the requirements of ASTM specifications E-9 and E-209. The platens and upper push rod were fabricated from Inconel S, and the remaining components exposed to elevated temperatures were fabricated from AISI 304 stainless steel.

The protective atmosphere surrounding the specimen was contained by a stainless steel sleeve which rested on the bottom platen of the subpress as shown in Figure 23. The top platen was free to slide inside the sleeve. Argon was metered into the chamber through an inlet in the bottom platen.

The furnace used for the compression tests was a split tube resistance-heated type. Temperature was controlled by a potentiometer-controller and a chromel-alumel thermocouple positioned within the furnace but outside the inert-atmosphere chamber, as shown in Figure 23. The temperature of the specimen was monitored with a direct-temperature read-out potentiometer and a chromel-alumel thermocouple in spring-loaded contact with the surface of the specimen.

Compression up to 0.2% was detected by a mechanism consisting of a 500X microformer extensometer that sensed motion between the top and the bottom platens of the testing machine. Compression beyond the 0.2% offset was measured from the relative motion of the crosshead and table of the machine with a 20X extensometer.

Load was detected by the pressure-sensitive weighing system of the Baldwin universal testing machine. The compression signal was recorded against load on the autographic recorder of the testing machine.

8.5.2 Test Procedure

Prior to testing, heating-rate and thermal-gradient studies were conducted. The heating trials showed that, at all test temperatures, the center of the specimen came to temperature equilibrium with the surface temperature within 5 minutes after the surface reached the test temperature.

The specimens for the compression tests were $\frac{1}{2}$ -inch in diameter and 1-inch long. The specimens were compressed at a nominal rate of 0.005 in./in./min to 50% deformation, and the com-

pression was recorded. The 0.2% offset yield strength and the apparent stress at 25% and 50% deformation were calculated from the recorded load-compression curves. Yield strengths were determined graphically by plotting the 0.2% offset. Compression strengths at 25% and 50% strain were calculated using the original cross sectional area of the specimens. The compression test data are listed in Table VII.

FIGURE 22 Arrangement of Furnace and Penetrator of Hot Hardness Tester

DWG. NO. 44-68

FIGURE 23 Arrangement of Specimen, Thermocouples, and Extensometer (Shown Schematically) for Compression Tests

TABLE VII Compression Properties of Uranium at Elevated Temperatures*

Process Used	Temperature (°F)															
	885		955		1025		1095		1150		1200		1250		1300	
	Specimen Direction, Longitudinal (L) or Radial (R)															
	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R
<u>Cast</u>																
0.2% Offset Yield Strength (psi)	13,100	10,900	7,900	9,300	6,700	7,000	5,600	5,000	4,000	4,400	3,400	3,400	—	—	8,800	8,200
Stress at 25% Offset (psi)	27,800	20,800	13,800	16,600	12,500	13,700	9,900	9,600	6,400	8,400	5,500	6,000	—	—	13,100	13,200
Stress at 50% Offset (psi)	41,500	34,800	23,900	28,000	19,500	22,600	13,400	14,400	9,200	12,900	8,800	10,200	—	—	20,400	20,400
<u>Cast and Beta Heat Treated</u>																
0.2% Offset Yield Strength (psi)	17,600	15,600	12,400	11,400	8,000	8,000	5,900	6,200	5,600	4,400	3,700	4,200	12,700**	12,600	9,800	8,900
Stress at 25% Offset (psi)	28,900	24,900	18,600	18,300	11,800	12,400	9,400	9,000	7,000	6,600	5,500	5,600	15,600**	15,800	12,800	12,400
Stress at 50% Offset (psi)	39,700	33,600	26,400	26,500	16,000	17,000	12,900	12,600	9,300	9,400	7,700	8,000	23,400**	23,400	19,200	19,100
<u>Extruded</u>																
0.2% Offset Yield Strength (psi)	11,100	12,200	8,800	9,400	5,600	5,900	4,100	4,800	3,600	4,100	3,000	3,200	12,300**	12,400**	10,200	8,800
Stress at 25% Offset (psi)	20,600	22,500	13,200	17,100	9,200	10,600	7,000	8,000	6,000	7,000	4,900	5,600	13,900**	13,900**	12,600	11,800
Stress at 50% Offset (psi)	29,100	32,700	19,000	25,800	13,200	16,000	10,800	12,600	9,200	10,700	7,500	8,600	20,200**	20,600**	18,400	18,400
<u>Extruded and Beta Heat Treated</u>																
0.2% Offset Yield Strength (psi)	15,800	17,900	12,000	12,400	8,200	8,600	6,600	7,100	5,400	5,300	4,400	3,700	12,600	12,600	10,100	10,600
Stress at 25% Offset (psi)	26,000	26,500	18,500	18,800	12,700	12,800	8,700	9,700	7,200	7,000	5,600	5,400	15,000	14,400	13,400	12,800
Stress at 50% Offset (psi)	35,600	37,700	27,200	26,400	17,700	18,200	11,800	13,700	10,200	10,100	8,100	7,900	22,000	21,400	20,400	19,400
<u>Rolled</u>																
0.2% Offset Yield Strength (psi)	10,400	11,800	7,800	8,700	5,200	6,200	4,400	4,600	3,200	3,500	2,700	2,900	—	13,000	10,100	10,200
Stress at 25% Offset (psi)	21,400	24,000	13,300	15,300	8,900	10,400	7,100	8,000	5,200	5,800	4,200	4,700	—	15,200	12,700	11,800
Stress at 50% Offset (psi)	31,000	35,500	20,500	22,600	13,800	15,600	11,400	12,700	8,400	9,600	7,100	7,800	—	22,400	18,700	18,200
<u>Rolled and Beta Heat Treated</u>																
0.2% Offset Yield Strength (psi)	17,800	17,200	12,600	11,700	8,600	9,000	7,000	7,000	5,200	5,400	4,200	4,000	13,200**	12,400	10,000	9,700
Stress at 25% Offset (psi)	29,400	27,000	18,300	18,200	12,700	13,400	9,800	9,800	6,600	6,900	5,100	5,400	15,200**	14,800	12,600	12,000
Stress at 50% Offset (psi)	40,200	38,200	25,000	25,500	17,600	18,800	13,500	13,700	9,400	10,100	7,400	7,900	22,300**	23,500	18,900	18,600

* All values are averages of two specimens unless otherwise noted.

** One specimen only.