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METALLURGY AND CERAMICS

MECHANICAL AND PHYSICAL PROPERTIES OF URANIUM
CHAPTER 8 OF NUCLEAR METALLURGY LECTURES

By

R. E. Hueschen

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MECHANICAL AND PHYSICAL PROPERTIES OF URANIUM

I. INTRODUCTION

A knowledge of the mechanical and physical properties of uranium is important in understanding and explaining its pile behavior. The effects of irradiation on the properties of uranium will be dealt with in another chapter. However, it is important to know and understand the pre-irradiation properties of uranium prior to investigating the effects of irradiation.

The properties of uranium are sensitive to orientation, which is controlled by prior heat treatment and fabrication history. This sensitivity to orientation is due to anisotropy, that is, the properties of uranium are dependent on the crystallographic direction in which the measurement is made. In as-rolled rod, for example, a large number of grains in this rod may be preferentially oriented in the rolling direction and certain properties, such as tensile and thermal expansion, will vary markedly dependent on whether the property is being measured in the transverse or longitudinal direction. Minor variations in chemical composition also are known to have a marked effect on mechanical properties. It is apparent, therefore, that orientation, chemical composition, voids, and inclusions will affect, either independently or in combination, the values obtained for any given property determination.

The anisotropy of uranium stems from its crystal structure. The room temperature phase is orthorhombic and this corrugated sheet or deformed close-packed, hexagonal structure is responsible for some of the unique properties exhibited by uranium. A few reference books on the subject of anisotropy, properties, plastic deformation, etc. are listed at the end of lecture.^(1,2,3,4,5) A comparison of a few mechanical and physical properties of uranium, zirconium, aluminum, and steel is given in Figure 1.

II. PHYSICAL PROPERTIES OF URANIUM

The physical properties, as distinguished from mechanical properties, include density, thermal and electrical conductivity, and thermal expansion. The physical properties of a metal arise from the interaction between the atoms and the electronic configuration of the atoms. In general, the stronger the binding force between the atoms, the lower the thermal expansion; and the greater the mobility of the electrons the greater the electrical conductivity. Some physical and chemical constants for uranium are given in Table I.⁽⁶⁾

A. Electrical Resistivity

An important electronic property of metals is electrical conductivity. In order to explain the good electrical conductance of metals, one must use the metallic bond concept in which there is a sharing of electrons (electron cloud) by the atoms. The free electrons are thus able to move throughout the lattice in definite energy levels while holding the atoms of the metal together. This mobility of electrons permits conduction when a potential is applied.

Electrical resistance arises from any condition which hinders this flow of electrons.

FIG. 1 COMPARISON OF SOME AVERAGE PROPERTIES OF BETA HEAT-TREATED URANIUM, ZIRCONIUM, ALUMINUM AND HOT-ROLLED MILD STEEL. STRENGTH, ELONGATION AND THERMAL CONDUCTIVITY VALUES AT ROOM TEMPERATURE. THERMAL EXPANSION COEFFICIENTS ARE AVERAGE VALUES FROM ROOM TEMPERATURE TO 600°C.

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TABLE I

PHYSICAL AND CHEMICAL CONSTANTS OF URANIUM⁽⁶⁾

Density, gm/cm ³	
Theoretical, from X-ray data	19.13
Wrought material	18.5-19.0
Pressed and sintered powder	18.9
Beta heat treated	18.9
Melting point, °C	1133 ± 1
Boiling point, °C	3900
Heat of fusion, kcal/mole	2.5-3.0
Heat of vaporization, kcal/mole	93
Specific heat, cal/(mole)(°C)	
-249.28°C	1.211
-201.61°C	4.657
-149.70°C	5.639
-99.57°C	6.053
-0.16°C	6.524
27°C	6.649
227°C	7.606
427°C	8.952
627°C	11.107
774 (β) °C	10.147
774 (γ) °C	9.177
827°C	9.147
Enthalpy (H _T), cal/mole	
27°C	1,539
127°C	2,202
227°C	2,935
327°C	3,725
427°C	4,583
527°C	5,520
627°C	6,567
727°C	8,337
827°C	10,430
Entropy, cal/(mole)(°C)	
27°C	12.052
127°C	13.941
227°C	15.601
327°C	17.056
427°C	18.387
527°C	19.646
627°C	20.882
727°C	22.760
827°C	24.761

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Four "roadblocks" to electrical conduction are as follows:

1. resistance by collision of electrons with vibrating atoms
2. the extent to which the electrons are bound to adjacent atoms
3. resistance caused by collision with foreign or impurity atoms
4. resistance from internal stress which disrupts the energy level at which the electron transfer occurs.

Temperature greatly influences the effects of the above items, particularly item number one.

Since electrical resistivity is an anisotropic property in single crystals, one would expect different resistivity values for uranium crystals in the three different crystallographic directions. Because of the difficulty in growing single crystals of uranium large enough to use, there is very little information available. However, the British⁽⁷⁾ have reported values obtained on pseudo-single crystals of uranium as shown in Table II.

TABLE II

ELECTRICAL RESISTIVITY OF URANIUM AS
A FUNCTION OF CRYSTALLOGRAPHIC DIRECTION

<u>Crystallographic Direction</u>	<u>Elec. Resis. - μ ohm-cm</u>
"a" [100]	25
"b" [010]	25
"c" [001]	32

Qualitatively, these results are checked by data on polycrystalline, as-rolled uranium in which the electrical resistance in the transverse direction is greater than in the longitudinal direction, the former direction containing more grains whose "c" axis is parallel to it.

The electrical resistivity of beta heat-treated uranium is 30×10^{-6} ohm-cm at room temperature. Lead and antimony have similar resistivities whereas aluminum and copper are much lower. The electrical resistivity of uranium increases with increasing temperature as one would expect with most materials primarily from the increasing effect of atomic vibrations.^(6,8,9) The change in electrical resistivity with temperature is shown in Figure 2.⁽⁸⁾

B. Thermal Conductivity

Thermal or heat conductivity is another predominantly electronic property of metals. In the case of thermal conductivity, heat is the applied potential and the electrons

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Figure 2. Electrical Resistivity of Uranium versus Temperature as Determined by Bennett. (8)

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are the principal heat conductors. However, the collisions of vibrating atoms add to the conductivity of heat through a metal. The "roadblocks" mentioned for electrical resistance also account for thermal resistivity. Thermal conductivity is also an anisotropic property in single metallic crystals. No thermal conductivity data are available as yet on uranium single crystals.

The value for the thermal conductivity of uranium at room temperature is 0.06 cal/cm-sec-°C or 0.25 watts/cm-sec-°C. The thermal conductivity increases with increasing temperature as predicted by the Wiedemann-Franz law

$$K/\sigma T = 2.45 \text{ watt-ohm/degree}^2$$

where K is the thermal conductivity in watts/cm sec °C, and σ is the electrical conductivity in micro-ohm⁻¹ cm⁻¹ and T is the temperature in °K.

The thermal conductivity of uranium as a function of temperature is shown in Figure 3 as determined by Danielson.⁽¹⁰⁾ Figure 3 also shows the predicted thermal conductivity as obtained by the Wiedemann-Franz law using the electrical resistivity data of Bennett.⁽⁸⁾ Additional thermal conductivity data on uranium is available at various temperatures.^(9,11,12,13,14) Deems and Nelson have determined the thermal conductivity of powder-metallurgy uranium.⁽¹⁵⁾

C. Thermal Expansion

When a piece of metal is heated, the increase in energy causes an increase in the amplitude of the atomic vibrations and the metal expands. Generally speaking, the stronger the binding force between atoms, the lower the coefficient of thermal expansion. The melting point of a metal is a rough approximation of resistance to thermal agitation and thus to bonding strength and expansion, but it is not as good a determination as one made on a solid metal since it involves the free energies of both the solid and liquid states. Thermal expansion is a useful tool in determining the degree of anisotropy of a given material. The large differences in uranium thermal expansion in each crystallographic direction results in twinned crystals and a stressed material even after annealing.

The thermal expansion of uranium is similar to copper but lower than aluminum. An average of five beta heat-treated samples gave the following equation for the linear coefficient of uranium at any temperature in degrees Centigrade,⁽¹⁶⁾

$$\alpha_t = \frac{1}{l_0} \frac{dl}{dt} = (13.4 + 0.0132 t) \times 10^{-6}/^{\circ}\text{C}$$

The value obtained from this equation is the slope of the tangent to the expansion-temperature curve at the temperature "t". It is the instantaneous, not the average, coefficient of thermal expansion. The average value of beta heat-treated uranium from room temperature to 600 C is 17.5×10^{-6} per °C. However, as shown in Figure 4, beta heat-treated uranium can vary from approximately $15\text{-}20 \times 10^{-6}$ in/in per °C.^(16,17) This variation is primarily due to the difficulty in obtaining completely random and completely stress-free polycrystalline beta heat-treated uranium, the stresses resulting to a large extent from its

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Figure 3. Thermal Conductivity of Uranium As Determined by Danielson⁽¹⁰⁾ and as Predicted from the Wiedeman-Franz Law using Bennetts' Electrical Resistivity Data.⁽⁸⁾

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Figure 4. The range of expansion versus temperature obtained for beta heat-treated uranium. (16,17)

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anisotropic contractions.

The thermal expansion of as-rolled polycrystalline uranium, because of its anisotropy, can vary from a negative value to a value of $28-30 \times 10^{-6}/^{\circ}\text{C}$ dependent on the direction in which the sample is obtained from the rod. The expansion can be very small or negative when a cold-rolled sample is measured in the direction parallel to rolling, or very large if the sample is measured in the transverse direction as shown in Figure 5. The low value is, of course, due to (010) poles ("b" axis) preferentially oriented in the longitudinal direction. The uranium rods rolled at higher alpha phase temperatures, however, do not show so large a variation in thermal expansion.⁽¹⁸⁾ The coefficients of thermal expansion for beta and gamma uranium are also shown in Figure 5.⁽¹⁹⁾

The thermal expansion of uranium as determined by BMI, and given in CT-2144 and RH-3, does not agree too closely. The BMI data⁽⁶⁾ for each crystallographic direction is given in Table III and the coefficients from CT-2144⁽²⁰⁾ are given in Figure 1. The expansion of polycrystalline as-rolled uranium would indicate that the data in Reference 6 is more correct.

TABLE III
THERMAL EXPANSION OF URANIUM AS
DETERMINED BY X-RAY TECHNIQUES (REFERENCE 6)

Direction parallel to axis of	Thermal Expansion $10^{-6}/^{\circ}\text{C}$		
	25-125 $^{\circ}\text{C}$	25-325 $^{\circ}\text{C}$	25-650 $^{\circ}\text{C}$
(100) plane	21.7	26.5	36.7
(010) plane	-1.5	-2.1	-9.3
(001) plane	23.2	23.9	34.2
Volume	45.8	48.6	61.5

$$100 \quad l_t = l_{27^{\circ}\text{C}} (1 + 17.2 \times 10^{-6} t + 30.8 \times 10^{-9} t^2)$$

$$010 \quad l_t = l_{27^{\circ}\text{C}} (1 - 9.2 \times 10^{-6} t + 40.4 \times 10^{-9} t^2 - 67.5 \times 10^{-12} t^3)$$

$$001 \quad l_t = l_{27^{\circ}\text{C}} (1 + 25.1 \times 10^{-6} t - 21.3 \times 10^{-9} t^2 + 57.5 \times 10^{-12} t^3)$$

$$\text{Volume } V_t = V_{27^{\circ}\text{C}} (1 + 45.0 \times 10^{-6} t - 3.4 \times 10^{-9} t^2 + 5.0 \times 10^{-12} t^3)$$

III. MECHANICAL PROPERTIES

Probably the most important and least understood characteristics of metals are their mechanical properties. It is only within the "perfect" elasticity range that the properties are well understood. In this range stress is proportional to strain, and, in fact, theoretical calculations which have been carried out from interatomic forces are in agreement with experiments. The plastic properties, however, are not nearly so well understood, although the dislocation theory as proposed by Taylor⁽²¹⁾,

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Figure 5. Thermal expansion curves of as-rolled uranium measured in the longitudinal and transverse rod direction to illustrate anisotropy of polycrystalline uranium.

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Polanyi⁽²²⁾, and Orowan⁽²³⁾ has qualitatively helped to explain these properties. Through the use of these specific lattice imperfections, work-hardening, critical shear stress, and some aspects of creep are qualitatively explained on the basis of this theory. The theory is difficult to check experimentally and as yet cannot predict results quantitatively. Fracture and strength are probably the least understood properties. The theoretical breaking stress of a material is about one thousand times greater than is obtained experimentally. These large discrepancies, both for yield and breaking strength, led to the imperfection theories which have and are being developed. Dislocation theory is a broad subject and references are listed in the back of the text for the interested reader.^(1,3,4)

Since the properties of even simple cubic metals are difficult to describe or predict, it is not surprising that uranium, with its pseudo-metallic structure, its imperfections, its impurities, and its anisotropy is not only difficult to predict but gives the variation in properties found through experiment.

A. Tensile Properties

When a metal is stressed, the atoms within the metal are displaced from their equilibrium position of lowest potential energy. If the stress applied is not too great, the atoms will return to their equilibrium position, and this is termed elastic deformation. If the critical stress for a given metal is exceeded, some atoms will not return to equilibrium position. When this occurs, unrecoverable plastic deformation has taken place.

The tensile test produces a stress-strain curve from which such properties as elastic modulus, yield strength, proportional limit, and energy of rupture are obtained. In most cases uranium exhibits a very short range in which stress is proportional to strain. An accurate elastic or Young's Modulus is, therefore, difficult to determine. Uranium deforms plastically to a slight degree under relatively low stress - sometimes in the neighborhood of 2000 psi. Typical stress-strain curves for beta heat-treated uranium are shown in Figure 6,⁽²⁴⁾ and the range of values exhibited by uranium after various fabrication histories are given in Table IV and Figure 7.^(25,26,6,18,27) The range of values obtained for rolled-annealed uranium again results, to a large extent from uranium's anisotropy. Some elongation and yield strength values are shown in Figure 8, 9, and 10 as a function of rolling temperature.^(27,6) The ultimate strength and elongation are particularly affected by voids, inclusions, and cracks. Uranium exhibits very little necking down during a tensile test and the reduction in area occurs primarily over the entire gage length of the sample. This lack of necking is responsible for the ultimate and breaking strength having essentially the same value.

(6,24,28,29)

The properties of beta heat-treated uranium at elevated temperatures are given in Figure 11 and 12 and the stress-strain curves obtained at various temperatures are shown in Figure 13.⁽²⁴⁾ There is evidence that uranium has a ductile to brittle transition temperature near room temperature^(24,29,30) and this phenomenon is being studied further.

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Figure 6. The cross-hatched band contains the stress-strain curves of eleven beta heat-treated tensile specimens tested at room temperature. (24)

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EFFECT OF HISTORY ON STRENGTH OF URANIUM. THE BAR CHART REPRESENTS RANGES OF ULTIMATE AND YIELD STRENGTHS FOR URANIUM IN THE AS-ROLLED, BETA HEAT-TREATED AND GAMMA-EXTRUDED CONDITIONS.

Figure 7

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EFFECT OF ANNEALING ON PROPERTIES OF ROLLED ROD.

Figure 8 (Reference 27)

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THE EFFECT OF THE ANGLE BETWEEN TENSILE SPECIMENS AND ROLLING DIRECTION ON THE YIELD STRENGTH OF URANIUM SHEET. HOT REDUCTION 82%, WARM REDUCTION 80%.
LOS ALAMOS. JULY 1, 1952.

Figure 9 - (Reference 6)

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THE EFFECT OF THE ANGLE BETWEEN TENSILE SPECIMENS AND ROLLING DIRECTION ON THE ELONGATION OF URANIUM SHEET. NORMAL URANIUM ROLLED CONTINUOUSLY IN ONE DIRECTION - HOT REDUCTION, 82 %, WARM REDUCTION, 80%. LOS ALAMOS JULY 1, 1952

Figure 10 - (Reference 6)

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ULTIMATE AND YIELD STRENGTHS VERSUS TEMPERATURE FOR BETA-HEAT TREATED AND CAST URANIUM.

Figure 11 - (Reference 24, 28, and 29)

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Figure 12. Elongation of beta heat-treated uranium as measured by tensile test at various temperatures. (24,29)

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Figure 13. Stress-strain curves of beta heat-treated uranium at various temperatures. (24)

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TABLE IV

TENSILE PROPERTIES OF URANIUM
DEPENDENT ON FABRICATION HISTORY

Property	Uranium Fabrication History		
	As Rolled*	γ Extruded	Beta Heat-Treated
Ultimate Tensile Strength - 10^3 psi	85 - 160	65 - 80	85 - 105
Yield Strength (0.2% offset) - 10^3 psi	29 - 90	15 - 29	29 - 37
Elongation - %	10 - 30	---	8 - 15
Reduction in Area - %	8 - 20	---	7 - 10
Modulus of Elasticity 10^6 psi	19 - 25	---	22 - 26

* In direction parallel to rolling direction. Specimens not necessarily obtained from standard rods.

B. Effect of Annealing on Tensile Properties

One of the many unique features of uranium is the fact that annealing of a rolled specimen results in a marked decrease in ductility as measured by tensile elongation as shown in Figure 8, 9, and 10. Ordinarily, most of many metals obtain maximum ductility after annealing. The decreased ductility on annealing rolled uranium is, of course, tied in again with its anisotropy. It was found from the same study(27) that after annealing the rolled samples there was a definite increase in the number of (130) planes perpendicular to the force or rolling direction. This means that when testing a tensile specimen in this same direction, after annealing, there are more (130) planes perpendicular to the force being applied which will not twin because the shear stress is zero, and one would expect less elongation to be obtained.

C. Effect of Carbon Content on Tensile Properties

Battelle Memorial Institute has investigated the effects of carbon content on the tensile properties of as-cast uranium. These results are summarized in Table V.(6)

D. Elastic Constants

The elastic constants of uranium have been determined by ultrasonic techniques at 25 and 300 C by Kammer, Vigness, and Cardinal of the Naval Research Laboratories. (31)

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TABLE V

THE EFFECT OF CARBON CONTENT ON TENSILE
PROPERTIES OF AS-CAST URANIUM (REFERENCE 6)

Material	Carbon Content ppm	Total Impurities ppm	Yield Strength (0.2% off-set) 10 ³ psi	Ult. Str. 10 ³ psi	Elongation in 2" - %	Young's Modulus 10 ⁶ psi
High Purity	60	260	20	52	8	23
High Purity	210	410	22	53	8	24
Normal	360	525	28	59	8	23
Normal	550	650	29	72	11	25
Normal	630	815	28	75	17	24
Normal	710	1000	28	70	12	23
Normal	820	925	25	62	9	30
Normal	1250	1800	25	74	10	24

Their work is reported in NRL-4264 and a summary of their work is reprinted in Table VI. The conversion from dynes per cm² to psi can be made by multiplying by 1.4×10^{-5} .

E. Fatigue Properties

The purpose of the fatigue test is to determine the resistance of a metal to cycles of repeated stress. During the fatigue test, slip occurs after repeated and sufficient stress is applied. In some cases a sufficient stress may be as little as one-half the elastic limit. As continued slip takes place, minute cracks form and spread, gradually reducing the area of sound metal. The end of such a minute crack is a region of highly localized stress and the crack continues to grow. The final fatigue failure occurs with little distortion or area reduction, that is, a brittle fracture results.

There has been little reported in the literature on the fatigue properties of uranium. BMI reports that alpha extruded uranium specimens failed after 1.2 to 2.5×10^5 cycles at 35,000 psi using a cantilever beam machine.⁽⁶⁾ Murphy of Ames reports values for beta heat-treated uranium as shown in Figure 14.⁽²⁹⁾

Coffin of KAPL reports much lower fatigue strengths for as-rolled uranium in the transverse direction than in the longitudinal direction. He attributes this difference in fatigue properties to the presence of longitudinal stringers.

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FATIGUE - S-N CURVE FOR URANIUM. (29)

Figure 14

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TABLE VI

SUMMARY OF ELASTIC CONSTANTS FOR URANIUM OBTAINED
BY ULTRASONIC TECHNIQUES (REFERENCE 21)

Uranium Specimen History	Youngs Modulus = E 10 ¹¹ dynes/cm ²		$\frac{1}{E} \frac{dE}{dt}$ 10 ⁻⁴ /°C	Shear Modulus 10 ¹⁰ dynes/cm ²		Poissons Ratio	
	°C		25-300°C	°C		°C	
	25	300		25	300	25	300
Heat Treated 600°C for 30 min.	18.1-18.2	15.5-15.6	5-5.4	7.6-7.7	6.3	0.19	0.24
Heat Treated at 720°C for 70 sec.	19.3-20.1	16.3-16.6	5.6-6.3	8.2-8.5	6.6-6.7	1.8-1.9	2.3-2.4
Rolled at 480°C	18.2	15.7	5.0	7.6	6.3	0.195	0.235
Rolled at 550°C	18.5	15.8	5.3	7.5	6.4	0.205	0.242
Rolled at 630°C	18.9	16.3	5.0	7.9	6.5	0.190	0.229

Coffin carried out these fatigue tests in the cyclic strain region near the calculated strain range which slugs receive during exposure, and concludes that a slug could rupture by fatigue during operation after 150 cycles. (32,33,34) Stetson and Winton also observed longitudinal cracking within a few hundred cycles. (35)

F. Hardness

(6,17,18,25,26,27)

The hardness of alpha-rolled uranium is given in Table VII.

These hardness values were all taken on the same sample and are presented to give the values obtained on uranium with different types of hardness testers. (6)

The hardness of alpha- and gamma-extruded uranium at various temperatures is given in Figure 15 (36) The range of values for as-rolled and beta heat-treated uranium at room temperature have been included in Table VII. Dependent on fabrication temperature, alpha-extruded uranium would also have a range of hardness values at room temperature similar to the as-rolled uranium as shown in Figure 15.

G. Shear Strength

The shear strength of some metals is approximately equal to one-half of the ultimate strength. For uranium the shear strength is greater than one-half

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Figure 15

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TABLE VII

HARDNESS OF ALPHA-ROLLED URANIUM

<u>Scale</u> (all readings on same sample)	<u>Transverse</u> <u>Specimen</u>	<u>Longitudinal</u> <u>Specimen</u>
Rockwell B	97	98
Rockwell G	80.5	83
Vickers (10-15 kg load)	220	240
Vickers (30-45 kg load)	---	250
Brinnell (calculated from R_B)	240	260
Knoop (200 gm load)	260	320
Knoop (500 gm load)	250	300
Knoop (1000 gm load)	240	320
Eberback (263 gm load)	270	300
Eberback (645.6 gm load)	260	290

HAPO results show a range of hardness for as-rolled uranium from Rockwell B 88 to Rockwell C 25, and the hardness of beta heat-treated uranium ranges from Rockwell B 88-93.

the ultimate and values obtained for uranium by BMI in various conditions of fabrication and heat treatment are given in Table VIII.(6)

TABLE VIII

THE SHEAR STRENGTH OF URANIUM*
(REFERENCE 6)

Condition **	Shear Strength, 10^3 lb/Sq. In.		
	1/8 in. diam.	1/4 in. diam.	3/8 in. diam.
As Cast	85	84	75
Cold Swaged	127	114	95
Cold Swaged as Above and Annealed at 1100° F	83	88	80
Rolled at 1110° F	80	79	77

* Normal uranium 430 ppm. total impurities.

** All samples tested at room temperature.

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H. Creep

Creep is the continued slow plastic deformation or flow of a metal under constant low values of stress well below the yield point of the metal being studied. Creep does not occur by a single mechanism. In addition to slip and twinning, there may be flow at grain boundaries and subgrains, as well as recrystallization and precipitation effects. Dislocation theory is also used to explain creep.^(1,3) If it is accepted that creep occurs by slip and that at high temperatures lattice vacancies are in continuous circulation, it is expected that slow deformation will occur under low loads.

The creep data obtained by BMI is summarized in Table IX. BMI has noted appreciable effects due to thermal cycling which occur during normal creep testing, they feel this throws considerable doubt on previous creep data.^(6,37) The BMI data are presented in Table X which shows the marked effect of various temperature cycles on the "creep" values obtained for uranium.⁽⁶⁾

I. Impact Strength

The impact test is a simple evaluation of the notch toughness as a summation of load and deformation and is primarily a notch test and not an impact or shock test. The test will indicate only that a given metal is or is not brittle at a given test temperature with a notch of given form or severity. The impact test is a positive method of obtaining a toughness value, but it is not a test of impact behavior since the notch dominates the test. The V-notch Charpy impact values obtained at various temperatures for uranium having different histories is presented in Figure 16.^(38,6)

IV. SUMMARY

This lecture by no means covers all the work which has been done concerning the properties of uranium. Some of the older work has been neglected because the history of the uranium tested was not known, and not because the work itself was not good. The work on beta heat-treated uranium has been emphasized in this report because it was felt to be of more value to HAPO people.

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TABLE IX

CREEP OF URANIUM AT 930°F (500°C)
(REFERENCE 6)

Annealing History*	Stress Lb/Sq.In.	Time Hr.	Total Deformation	Minimum Secondary Creep Rate %/Hr.	Grain Size After Test, mm
10 Hr. at 1290°F	2750	1530	3.72	0.0025	--
and 10 hr. at 1110°F	2220	1200	2.20	0.0013	0.12-0.13
	1720	1700	0.82	0.0003	0.10-0.11
	1500	1515	0.85	0.00035	---
10 Hr. at 1110°F	2220	1200	4.72	0.0018	0.045-0.05
	1720	1350	1.92	0.0009	0.05-0.055

* All specimens 1110°F Rolled.

TABLE X

EFFECT OF THERMAL CYCLING ON CREEP OF URANIUM*
(REFERENCE 6)

Stress Lb/Sq.In.	Test Temperature Cycle °C	Deformation at 450 Hr, %	Creep Rate at 450 %/Hr.
1500	1.5 (499.25 to 500.75)	0.51	0.0012
1500	7 (493 to 500)	2.35	0.0036
1500	28 (472 to 500)	6.00	0.0136

* All specimens 1110°F rolled and annealed 10 Hr. at 1110°F.

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Figure 16
(Reference 6,38)

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