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DP - 139

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MECHANICAL PROPERTIES OF STRIATED URANIUM SLUGS

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Printed for
The United States Atomic Energy Commission
Contract AT(07-2)-1

ABSTRACT

Nonmetallic inclusions, which are described as "striations," have no adverse effect on the tensile, impact, torsion, or fatigue strength of uranium slugs. Mechanical properties of the slugs are primarily dependent on crystallographic orientation, which may be varied by heat treatment of the metal.

External Distribution according to
TID-4500(9th Ed.)

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MECHANICAL PROPERTIES OF STRIATED URANIUM SLUGS

INTRODUCTION

When a uranium billet that contains segregated impurities is rolled into a rod, the impurities are elongated into longitudinally oriented stringers. These stringers, or "striations," become visible when the slugs are pickled in nitric acid. Such striations occurred frequently in metal that was rolled during 1952 and 1953.

Tests that simulate the conditions under which the slugs are used had shown that striations produce undesirable effects; in addition, a compression test described in the Appendix had shown that striated slugs split when compressed endwise. It was not known, however, whether striations affect the common mechanical properties as ordinarily determined. Therefore, the present work was undertaken to compare the tensile, impact, fatigue, and torsion properties of striated uranium slugs with those of unstriated slugs. The work was done between May and September 1953.

SUMMARY

No significant difference between striated and nonstriated uranium was revealed by torsion, impact, tension, and fatigue tests. Therefore, these conventional tests offer no insight into the deleterious effects of striations that have been demonstrated by specialized techniques.

The mechanical properties were influenced by the orientation of the specimen with respect to rolling direction, and by the heat treatment of the specimen:

Samples oriented parallel to the rolling direction had higher tensile and impact strengths than did transversely oriented samples.

Alpha-rolled uranium had higher tensile strengths, but lower impact strengths, than did beta-transformed metal.

In the torsion test, a greater torque was required to fracture alpha-rolled samples than was required for beta-transformed samples.

DISCUSSION

BACKGROUND

In compression tests made at the Savannah River Laboratory in late 1952, short sections of striated slugs split longitudinally when compressed along their longitudinal axes. Sound, or nonstriated slugs did not split when subjected to the same deformation, as shown in the Appendix. The compression test revealed deficiencies in the properties of striated uranium, although the true significance of the test was difficult to interpret.

In many common metals, longitudinally oriented stringers or inclusions have a marked effect on the transverse mechanical properties of the material[1][2]. For example, a free-machining steel contains inclusions of manganese sulfide that are elongated in the direction of rolling. In this case:

The per cent reduction of area obtained in a tensile test is lower in a transverse sample than in a longitudinal sample.

The impact strength is lower in a transverse sample.

The fatigue strength is lower in a transverse sample.

On this basis, transverse and longitudinal mechanical properties of striated and nonstriated uranium slugs were investigated.

MATERIALS

Striated and nonstriated slugs of uniform quality throughout, illustrated in Figure 1, were selected from typical uranium slugs supplied in late 1952 and early 1953. Both alpha-rolled and beta-transformed material were obtained in the form of slugs. The flowsheet of experimental samples is shown in Figure 2.

Subsequent improvements in production methods, combined with closer inspection by the supplier, have reduced the number of rejected striated slugs to a negligible number.

Because the test specimens were machined from slugs one inch in diameter, the tensile, impact, and fatigue specimens were limited to one inch in length, and therefore could not conform to standard ASTM specifications[3]. Tensile specimens were shorter in length and diameter than standard-size samples. Impact specimens were standard with respect to the notch and cross section, but were shorter in length than the accepted standard. The fatigue specimens were one-half the standard width. Sketches of the test specimens are shown in Figure 3.

EQUIPMENT

The following standard mechanical testing equipment was used:

Tensile Tests:	Baldwin Tensile Machine
Impact Tests:	Sonntag Impact Tester
Fatigue Tests:	Sonntag Universal Fatigue Testing Machine
Torsion Tests:	Tinius-Olson Torsion Tester, situated at the Georgia Institute of Technology

PROCEDURES AND RESULTS

Tensile Tests

Procedure

The effect of striations was investigated by measuring the tensile strength and reduction of area in tensile specimens oriented in the longitudinal and transverse directions relative to the direction of rolling.

Thirty-six tensile samples were broken in the 120,000-pound Baldwin tensile machine. The specimens were aligned, and drawn tight by preloading. The load was applied at a rate of 400 pounds per minute until fracture occurred. The tests were run at room temperature, 72 to 79°F.

Results

Metal quality did not affect the ductility as measured by per cent reduction of area, as shown by the following table:

REDUCTION OF AREA OF ALPHA-ROLLED AND BETA-TRANSFORMED URANIUM

Heat Treatment	Orientation of Specimen	Reduction of Area, per cent	
		Nonstriated	Striated
beta	longitudinal	8.5	8.1
beta	transverse	5.2	5.4
alpha	longitudinal	17	14
alpha	transverse	2.1	2.5

If the striations had been deleterious to the tensile properties, the reduction of area in the transverse direction would have been noticeably lower for striated metal than for good metal.

Metal quality also had no significant effect on the ultimate tensile strength, as shown by the data in Table I.

Furthermore, striations did not cause cracks or fissures to appear on the surface of the fractured samples.

However, the tensile properties were influenced by the preferred crystallographic orientations in the uranium. This was demonstrated by the observation that the wide differences in longitudinal and transverse properties of alpha-rolled metal are markedly reduced when the metal is given a more random crystallographic structure by subjecting it to beta transformation.

By combining the data given in Table I for nonstriated and striated uranium, the effects of heat treatment and specimen orientation can be shown:

EFFECT OF HEAT TREATMENT ON THE AVERAGE TENSILE PROPERTIES OF URANIUM

Heat Treatment	Orientation of Specimen	Average Ultimate Tensile Strength, psi	Average Reduction of Area, per cent
alpha	longitudinal	121,000	16
	transverse	105,000	2
beta	longitudinal	92,000	8
	transverse	87,000	5

Impact Tests

Procedures

Impact tests were made on longitudinal and transverse specimens of striated and nonstriated uranium.

Eighty specimens were broken in a Sonntag Impact Tester. The velocity of the pendulum at impact was 17 feet per second. The holder for Izod samples[(3)] was modified to accommodate specimens of nonstandard length. The geometry of the modified holder was such that the striking edge of the pendulum struck the specimen at a point 3/16 inch above the notch. The center of the notch was at the top surface of the holder.

Specimens were tested at -50, 0, 100, and 145°F. The samples were immersed in a constant-temperature bath for at least 15 minutes; a dry ice - acetone bath was used for low temperatures, and a Dow-Corning 703 Silicone Oil bath for the higher temperatures. After the soaking period, the specimen was quickly transferred to the impact machine and broken. The elapsed time from leaving the bath to breaking the specimen was three seconds or less.

Duplicate samples of longitudinal and transverse specimens were broken at each temperature shown in Table II.

Results

The presence of striations did not affect either the longitudinal or transverse impact strengths of the uranium samples. The variation among supposedly duplicate specimens was as large as any difference between nonstriated and striated metal. Impact strengths of alpha-rolled and beta-transformed uranium are shown in Figures 4 and 5, respectively.

Visual examination of the fractured surface provided information on the grain size and inclusion content of the metal. The alpha-rolled material had a fine-grained fracture, and beta-transformed material had a coarse-grained fracture. The fractured surfaces of the transverse striated specimens had a lamellar structure with transverse lines parallel to the notch. Although the striated and nonstriated specimens fractured differently, there was no significant difference in the impact energy that was required to fracture the specimens.

The orientation of the specimen had a measurable effect on the impact strength. The absorption of energy was greater in the longitudinal direction for both alpha-rolled and beta-transformed uranium. To facilitate comparison between longitudinal and transverse specimens, average impact energies were used to obtain data for Figure 6. The inordinately high energy absorptions shown in Figure 4 were omitted in determining Figure 6. This procedure was justified because a visual examination of the fractured specimens indicated that these high values were caused by improper operation of the specimen holder.

Heat treatment had a significant effect on the impact strength of uranium. Beta-transformed uranium was tougher than alpha-rolled metal, especially at the higher temperatures. None of the beta-transformed longitudinal specimens broke at 145°F.

Because the impact tests were made on nonstandard specimens, the impact strengths are relative, rather than absolute. The conclusions in this report depend on qualitative comparisons between the various sets of specimens. The impact strengths obtained with the small specimens were higher than would have been obtained with standard specimens.

The results of this study agree qualitatively with results of Charpy impact tests made at Battelle[(4)(5)]. Although the numerical data were not directly comparable, the same trends of behavior were noted. For example, no sudden transition from ductile to brittle behavior was obtained as the temperature was lowered from 150 to -50°F, and the impact strength of beta-transformed material was higher than alpha-rolled material, especially at higher temperatures.

Torsion Tests

Procedure

Torsion tests of uranium bars were made to investigate the effect of shear stresses and strains on striated and nonstriated uranium.

One-inch round bars were twisted in a Tinius-Olson Torsion Tester of 60,000 inch-pound capacity. The length of the bars was such that the jaws were 2-1/2 inches apart. Because some deformation took place in the grips, the gage length used in calculations was greater than the distance between the jaws. The actual gage length was determined by drawing a straight line on each bar before testing, and then measuring the length of the bar on which the line was twisted.

The angle of twist in degrees was read on the movable head of the machine. The angle was read at each 500 inch-pounds of torque.

Eight bars were twisted to fracture. Fifteen samples were twisted to a torque of 20,000 inch-pounds. Samples were twisted at a rate of five degrees per minute below 8000 inch-pounds of torque, and at a rate of 20 degrees per minute above 8000 inch-pounds.

Results

Striations did not adversely affect torsional properties. Figure 7 shows typical torque-strain curves for alpha-rolled samples and beta-transformed samples; data for striated and nonstriated specimens were superposable on both curves. No fissures were visible on surfaces of striated pieces, although fiber stresses of approximately 150,000 psi were obtained. The fractured surfaces of broken bars of striated and nonstriated material were similar.

Beta transformation reduced the ductility of uranium in the torsion test, although in the tensile and impact tests beta transformation had improved the ductility. Figures 7 and 8 show that alpha-rolled samples exhibited better ductility than beta-transformed specimens. For example, at a torque of 14,000 inch-pounds, alpha-rolled samples twisted more than beta-transformed samples. Torques at fracture were greater for alpha-rolled samples than for beta-transformed samples.

Results of the individual tests are given in Table III. The calculation of torsion test results is explained in the Appendix. Measured and calculated data are summarized in the following table:

SUMMARY OF TORSION TEST RESULTS

Metal Treatment	Metal Quality	Torque at Fracture, in.-lb	Angle of Twist at Fracture, degrees	Angle of Twist at 20,000 in.-lb Torque, degrees	Strain-Hardening Coefficient	Strength Coefficient, psi
alpha	striated	23,000 (a)	560 (a)	353	0.27	176,000
alpha	nonstriated	24,100 (a)	550 (a)	290	0.26	185,000
beta	striated	19,800 (b)	310 (b)	323 (a)	0.32	225,000
beta	nonstriated	20,000 (a)	319 (a)	312	0.32	223,000
alpha	nonstriated	24,000 (d)	605 (d)	367 (c)	0.23	166,000
alpha	cracked	20,000	-------	390	0.26	166,000

(a) one sample
(b) average of two samples
(c) included bars not pickled, pickled once, pickled four times
(d) average of three samples

A relationship exists between stress and strain for plastic flow that can be generalized for all states of stress[6]. The stress and strain functions that accomplish this are called "effective stress" and "effective strain," which are related by the following equation:

$$\bar{\sigma} = K\bar{\delta}^n$$

where $\bar{\sigma}$ = effective stress

K = strength coefficient

$\bar{\delta}$ = effective strain

n = strain-hardening coefficient

This means that the $\bar{\sigma}$ vs. $\bar{\delta}$ curve for a given material is the same regardless of the stress system employed. Thus, the constants K and n may be regarded as fundamental constants of plastic flow for the material. Figure 8 shows that the slope of the curve, n, for the beta-transformed material is higher than that for alpha-rolled material. However, the values of K for beta-transformed samples also were higher. This is in disagreement with the general observation[7] that as the strain-hardening exponent, n, decreases, the strength coefficient, K, increases.

Bars were also tested in torsion to ascertain whether or not uranium was subject to hydrogen embrittlement (decreased ductility caused by an absorption of hydrogen by the metal) as a result of the pickling process. Presumably, atomic hydrogen formed during pickling could diffuse into the metal and decrease the ductility. Samples that were rolled, pickled once, and pickled four times were tested in torsion. The bars were pickled by immersion in 45 to 55 weight per cent nitric acid at 50 to 60°C for one minute. The data in Table III indicate that pickling does not produce hydrogen embrittlement, as measured by torsion tests.

Longitudinal cracks in alpha-rolled slugs lowered the torque at fracture. Three specimens containing internal longitudinal cracks were tested. One specimen fractured at an applied torque of 23,600 inch-pounds, which was comparable to the strength of a sound alpha-rolled sample. A longitudinal crack located at the center of this sample had little effect on the torque at fracture. The other two specimens, which contained cracks away from the center of the bar, fractured at torques lower than those normal for alpha-rolled material.

Fatigue Tests

Procedure

Tests were run on striated and nonstriated uranium to study the effect of metal quality on the ability of the metal to withstand fatigue. Sixteen flat longitudinal samples were used.

The samples were broken on a Sonntag Universal Fatigue Testing Machine. Bending stresses ranged from 20,000 to 48,000 psi. The samples were flexed so that the stresses alternated equally (in magnitude) between tension and compression.

Results

No significant difference between striated and nonstriated uranium was observed in fatigue tests of beta-transformed samples. The data are summarized in Table IV.

The S-N curve for beta-transformed samples is shown in Figure 9. The curve may be expressed by the equation:

$$S = CN^n$$

where S = bending stress

N = number of cycles

C = stress coefficient, found by extending the S-N line to $N = 1$

n = slope of the curve

From Figure 9, C = 155,000 psi and n = -0.104 for beta-transformed uranium. These constants for uranium are compared to the same constants for other materials in the following table.

FATIGUE CONSTANTS FOR VARIOUS MATERIALS[8]

Material	C, psi	n
uranium, beta-transformed	155,000	-0.104
bar copper	36,000	-0.08
cast iron	29,000	-0.09
annealed mild steel	66,000	-0.11

The fatigue limit is defined as the stress at which the curve on the S-N plot becomes horizontal. The fatigue limit was not reached for beta-transformed uranium at the lowest stress level (30,000 psi) used in this study.

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APPENDIX

DESCRIPTION OF THE COMPRESSION TEST

Introduction

Striations are formed by the elongation of segregated impurities in the direction of rolling, and they create planes of weakness parallel to the direction of rolling. These defects can be revealed by applying stress perpendicular to the planes of weakness. The desired stress may be produced by compressing a short cylinder of the metal, which bulges at its mid-point, and develops circumferential elongations as great as 25 per cent at the center of the bulge.

Procedure

1. A section about 1-1/2 inches long is cut from the slug, which is approximately one inch in diameter.

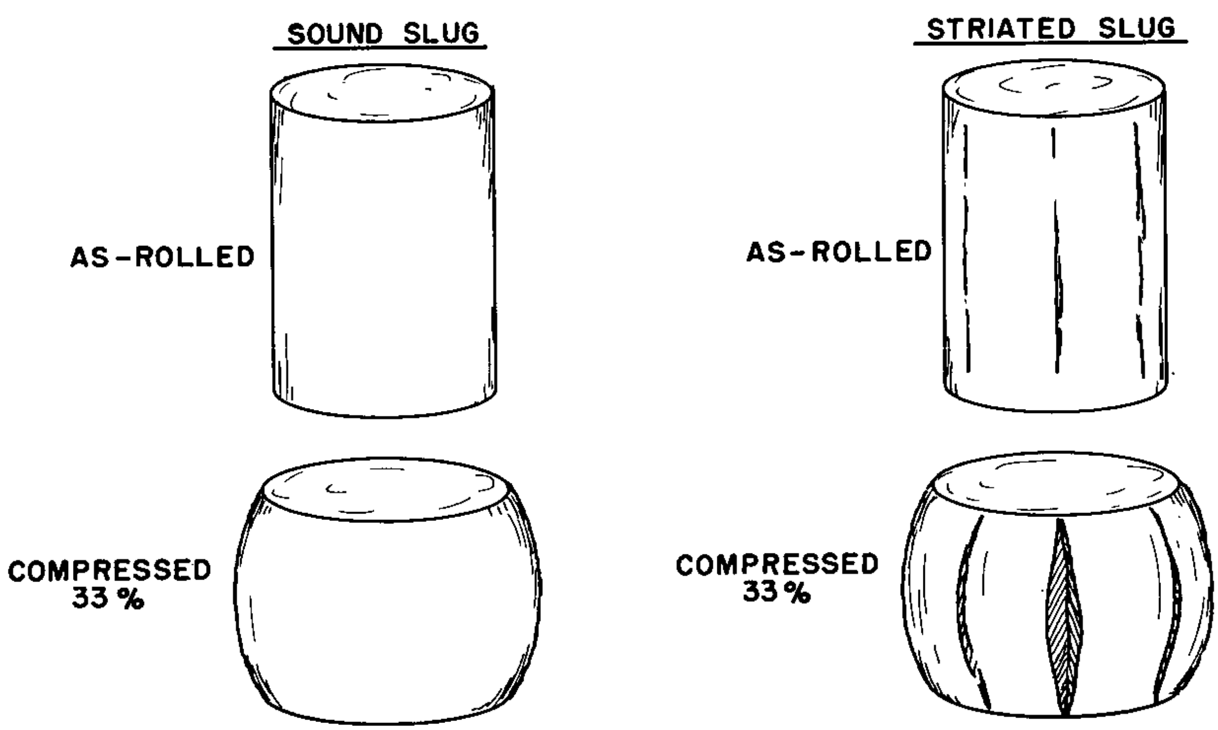
2. Thin sheets of lead, about 0.005 inch thick, are placed on each end of the specimen. The lead lubricates the ends of the specimen and permits more uniform deformation along the length of the specimen.

3. The specimen is compressed at room temperature until the length has been reduced to one inch.

4. The slug is compressed at a rate of 0.1 - 0.02 inch per minute; a load of about 120,000 - 150,000 pounds is required.

Results

Striated slugs in as-rolled condition split longitudinally, as shown below. No splitting was observed with nonstriated slugs. Striated slugs which had been beta-treated were much more ductile than the as-rolled ones, and the splitting was considerably less severe.



SAMPLE CALCULATION OF TORSION TEST RESULTS

The shear stress at the surface of a cylindrical test bar at any given torque can be calculated from the formula

$$\tau = \frac{(3T + \theta dT/d\theta)}{2\pi a^3}$$

where
τ = shear stress, psi
T = torque, in-lb
a = radius of bar, inches
θ = angular twisting, radians per inch

For this investigation

$$a = 1/2 \text{ inch}$$

Thus

$$\tau = \frac{8(4T-T_o)}{2(3.1416)} = 1.273(4T-T_o)$$

From Figure 7, Point A

T = 15,500 in-lb
T_o = 10,500 in-lb
τ = 1.273(62,000-10,500)psi
τ = 65,600 psi

The nominal shear strain is calculated from the formula

$$\gamma = \frac{a\theta'}{\ell}$$

where
γ = shear strain, radians
a = radius of bar, inches
θ' = angle of twist, radians
ℓ = gage length, inches

Since a = 1/2 inch, the shear strain can be calculated from the formula

$$\gamma = \frac{\theta'}{2 \times 57.3\ell} = \frac{\theta'}{114.6\ell}$$

For point A, Figure 7

T = 15,500 in-lb
θ' = measured in degrees = 137 degrees
ℓ = 5.6 inches

$$\gamma = \frac{137}{114.6 \times 5.6} = 0.213 \text{ radian}$$

Effective stress and effective strain are defined as follows(7):

$$\text{Effective Stress} = \bar{\sigma} = \frac{1}{\sqrt{2}}\left[(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2\right]^{1/2}$$

$$\text{Effective Strain} = \bar{\delta} = \sqrt{\frac{2}{3}}\left[\delta_1{}^2 + \delta_2{}^2 + \delta_3{}^2\right]^{1/2}$$

Where σ_1, σ_2, σ_3 are principal stresses
δ_1, δ_2, δ_3 are the principal strains

The above equations can be applied to torsion data as follows:

<u>Stress</u>

$$\bar{\sigma} = \frac{1}{\sqrt{2}} \left[(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2\right]^{1/2}$$

for torsion $\sigma_1 = -\sigma_3$, $\sigma_2 = 0$

$$\bar{\sigma} = \frac{1}{\sqrt{2}} \left[\sigma_1^{\,2} + \sigma_1^{\,2} + (2\sigma_1)^2\right]^{1/2} = \sqrt{3}\,\sigma_1$$

Shear Stress = $\tau = \frac{\sigma_1-\sigma_3}{2} = \sigma_1$

Therefore $\bar{\sigma} = \sqrt{3}\,\tau$

<u>Strain</u>

$$\bar{\delta} = \sqrt{\frac{2}{3}} \left[\delta_1^{\,2} + \delta_2^{\,2} + \delta_3^{\,2}\right]^{1/2}$$

for torsion $\delta_1 = \delta$, $\delta_2 = 0$, $\delta_3 = -\delta_1$

$$\bar{\delta} = \sqrt{\frac{2}{3}} \left[\delta_1^{\,2} + 0 + \delta_1^{\,2}\right]^{1/2} = \frac{2}{\sqrt{3}}\,\delta_1$$

Shear Strain = $\gamma = \delta_1 - \delta_3 = 2\delta_1$

Therefore $\bar{\delta} = \frac{\gamma}{\sqrt{3}}$

EXAMPLES

<u>Stress</u>

T = 15,500 inch-pounds
τ = 65,600 psi

$\bar{\sigma} = \sqrt{3}\,\tau = \sqrt{3}(65{,}600)$psi
$= 113{,}600$ psi

<u>Strain</u>

$\gamma = 0.213$ radian

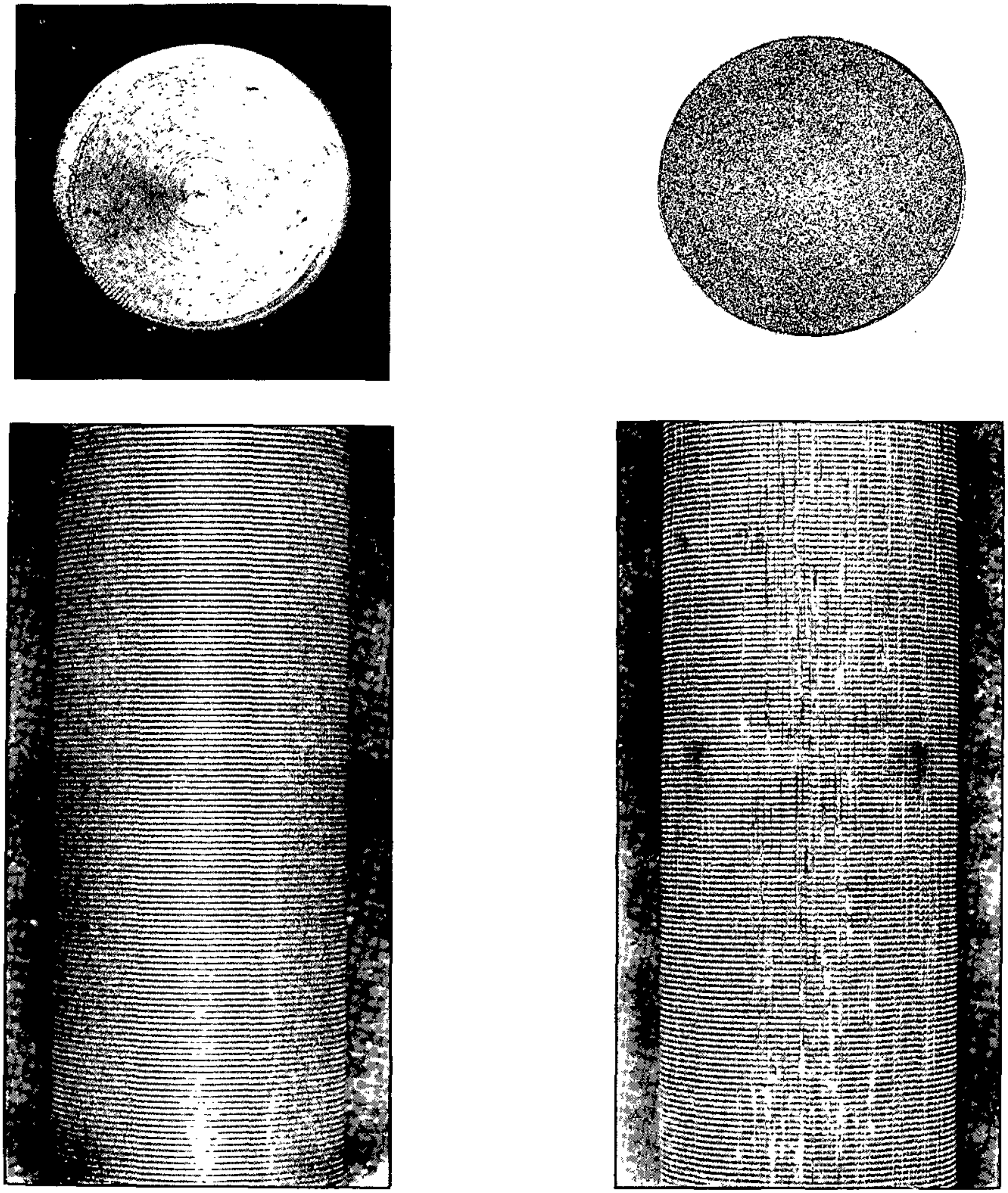
$\bar{\delta} = \frac{\gamma}{\sqrt{3}}$

$= \frac{0.213}{1.732}$

$= 0.125$ radian

These are represented by point A', Figure 8.

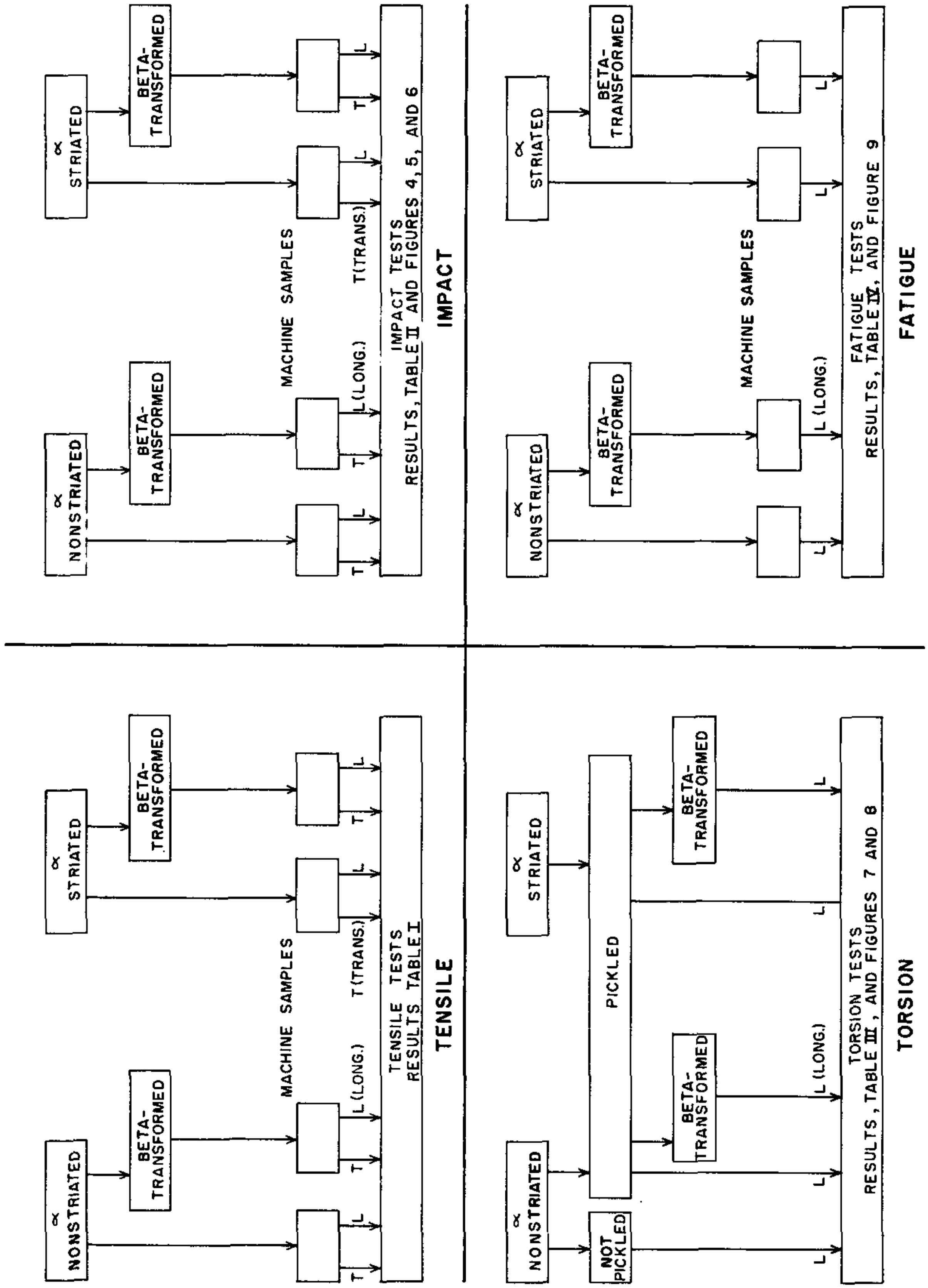
FIGURE 1



NONSTRIATED URANIUM STRIATED URANIUM

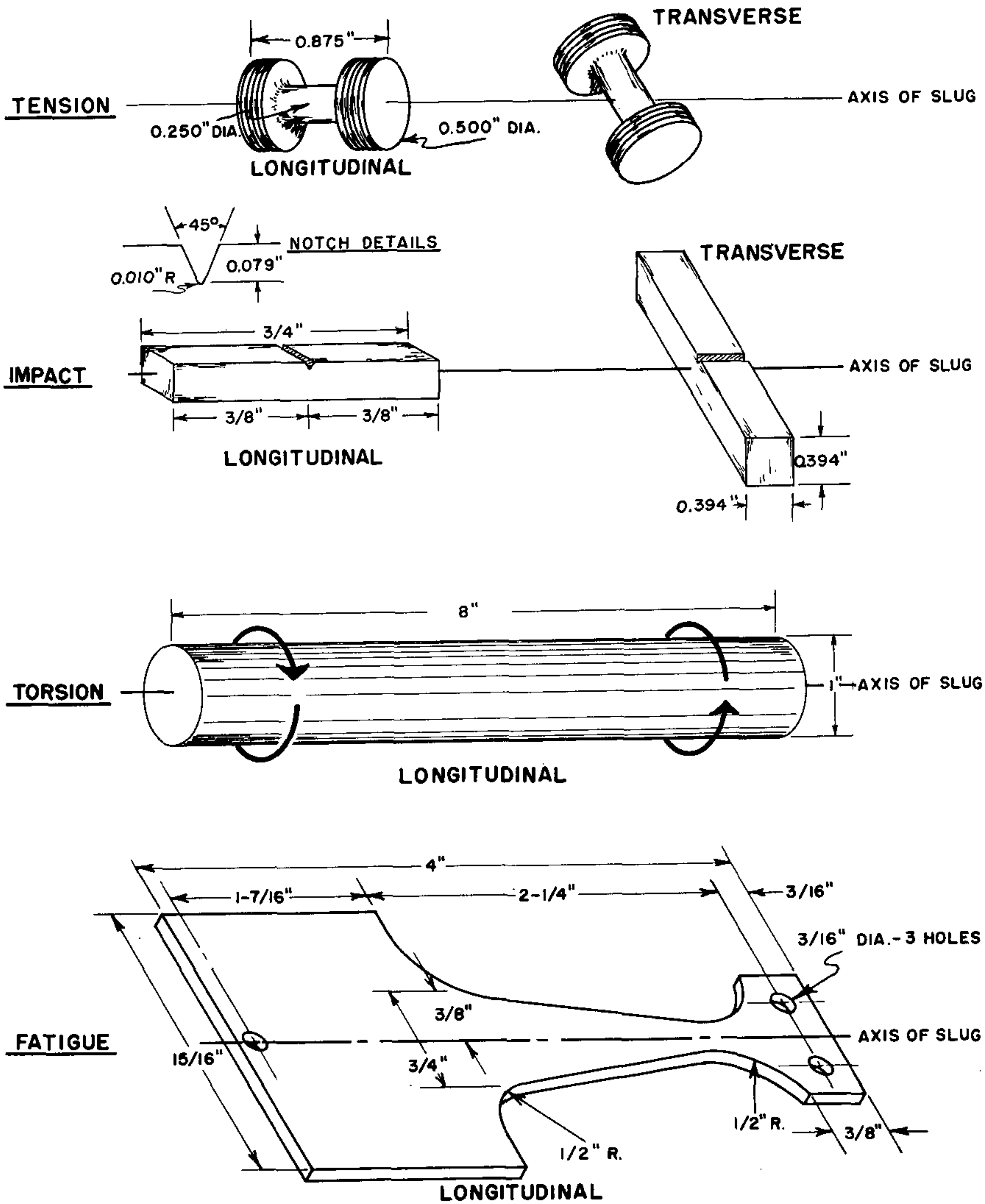
PHOTOGRAPHS OF URANIUM SLUGS

FIGURE 2



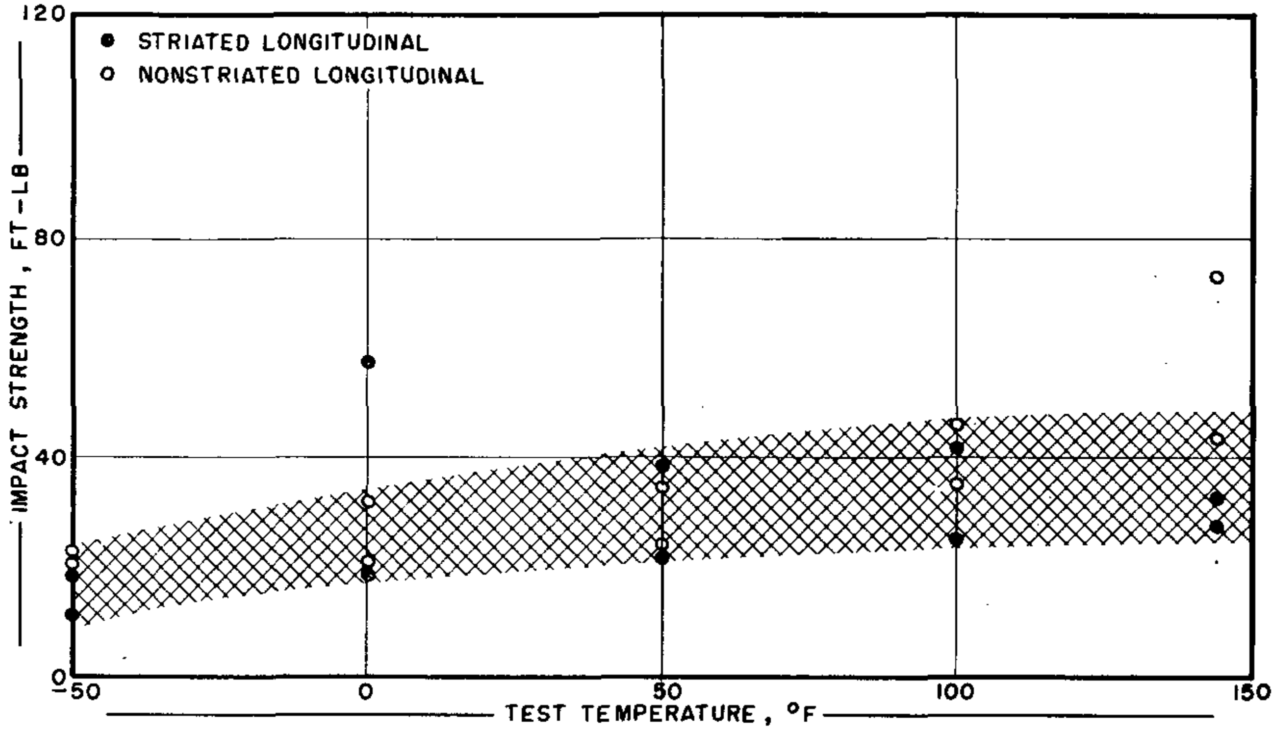
FLOWSHEET OF MATERIALS

FIGURE 3

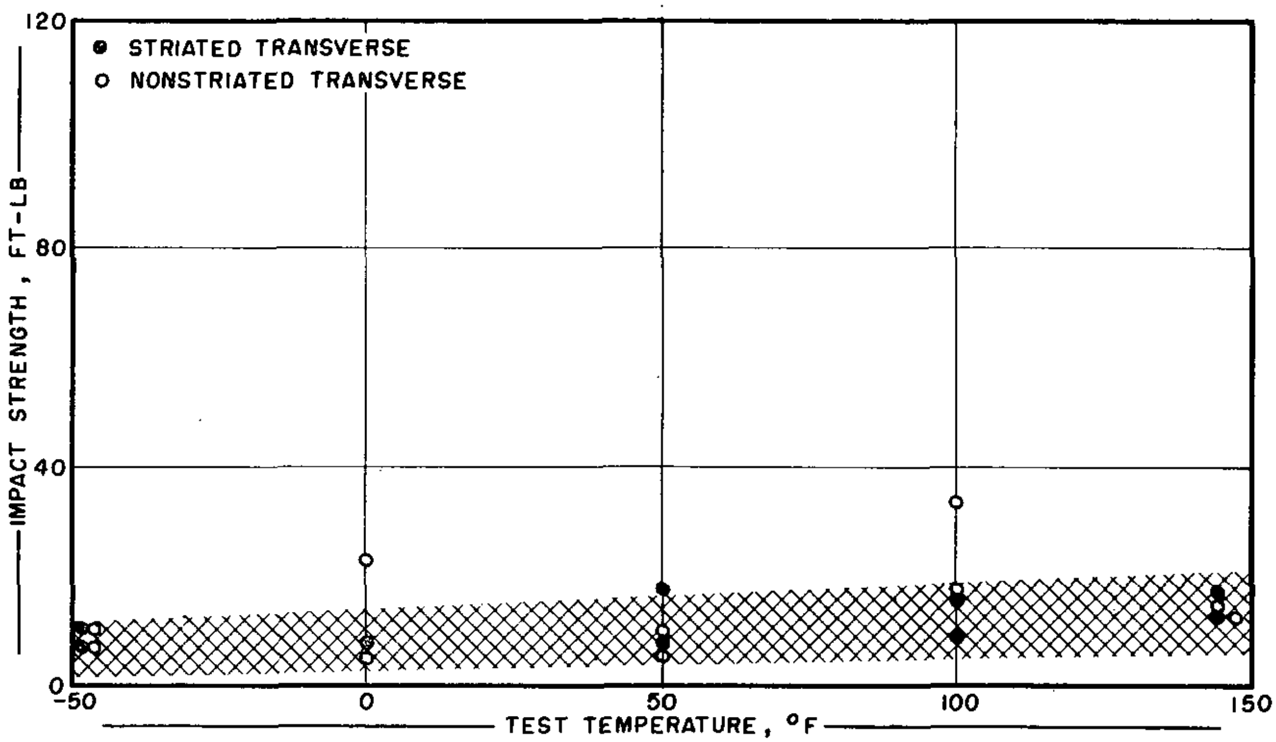


DESCRIPTION OF TEST SPECIMENS

FIGURE 4



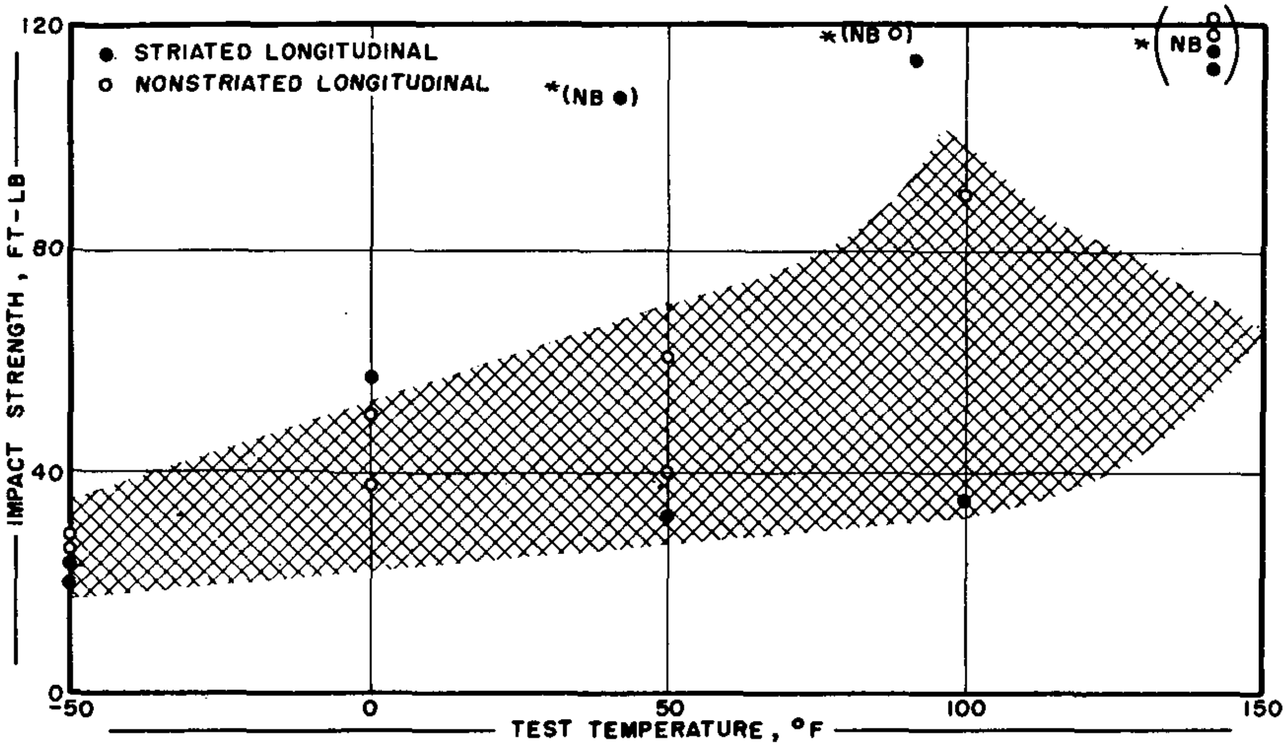
A. LONGITUDINAL SPECIMENS



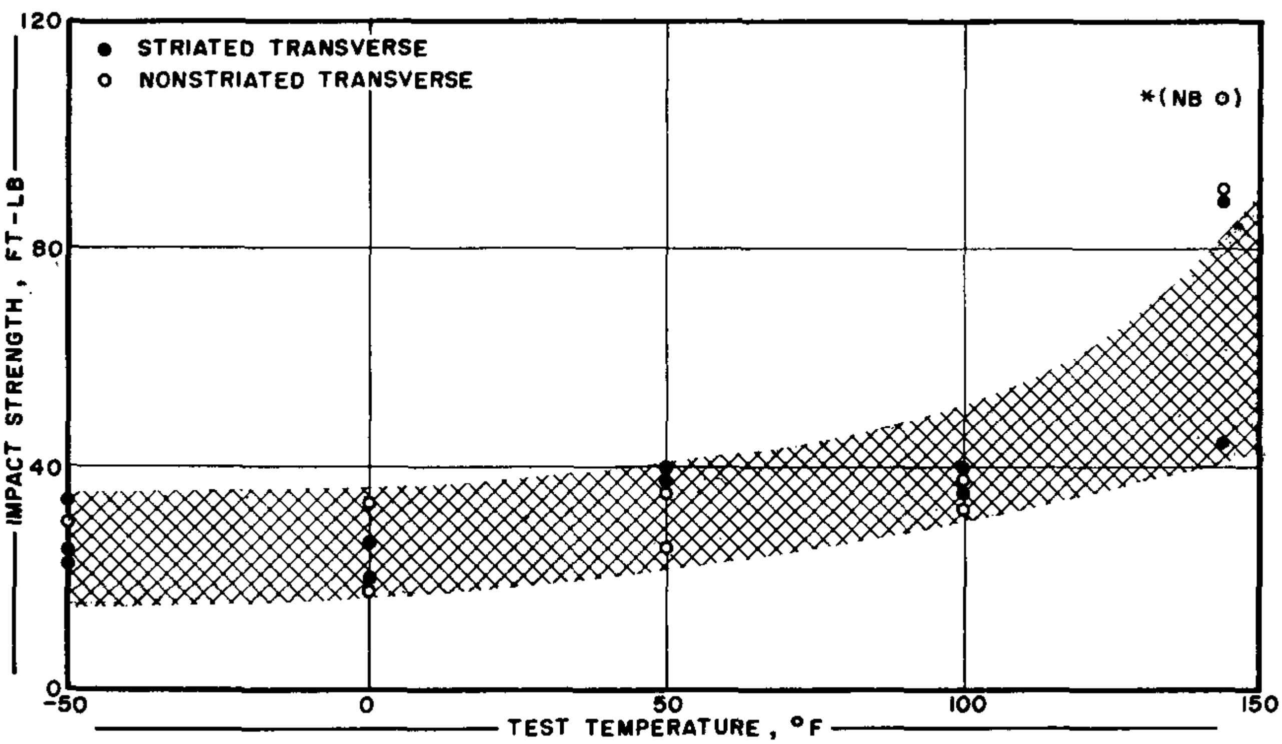
B. TRANSVERSE SPECIMENS

IZOD IMPACT STRENGTH OF ALPHA-ROLLED URANIUM

<u>FIGURE 5</u>



A. LONGITUDINAL SPECIMENS

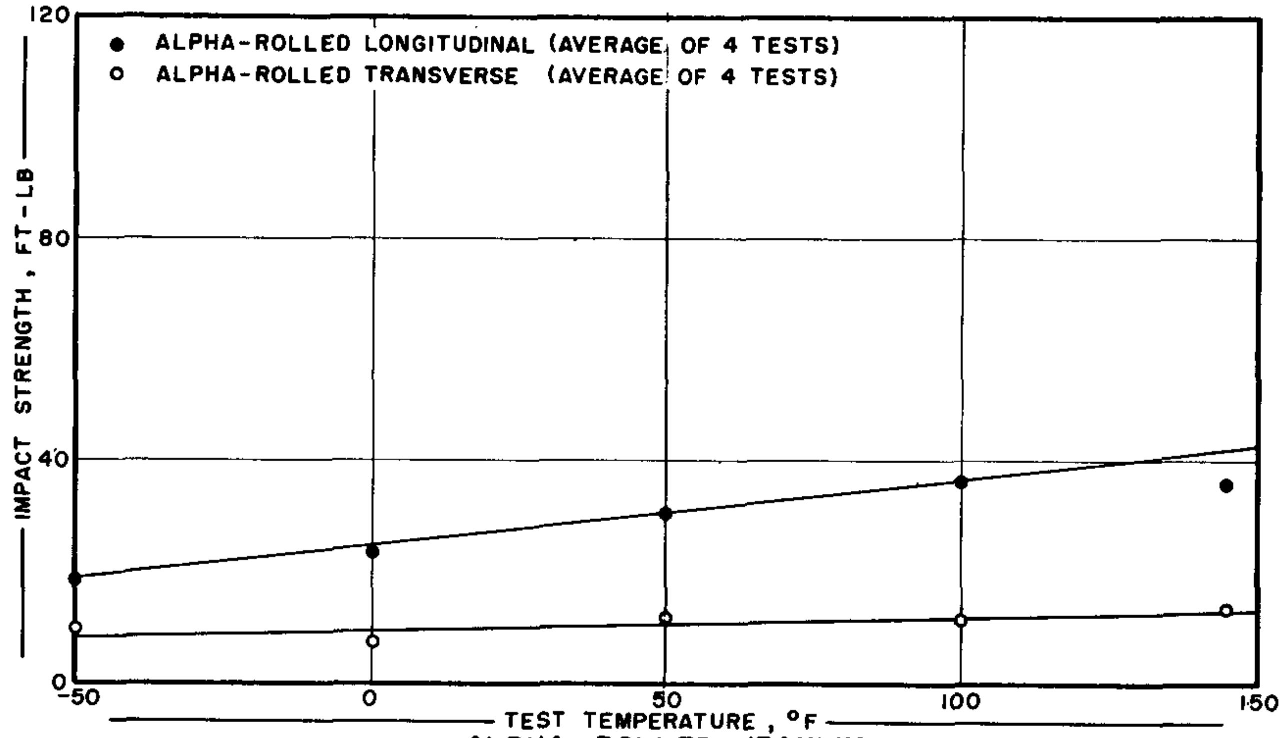


B. TRANSVERSE SPECIMENS

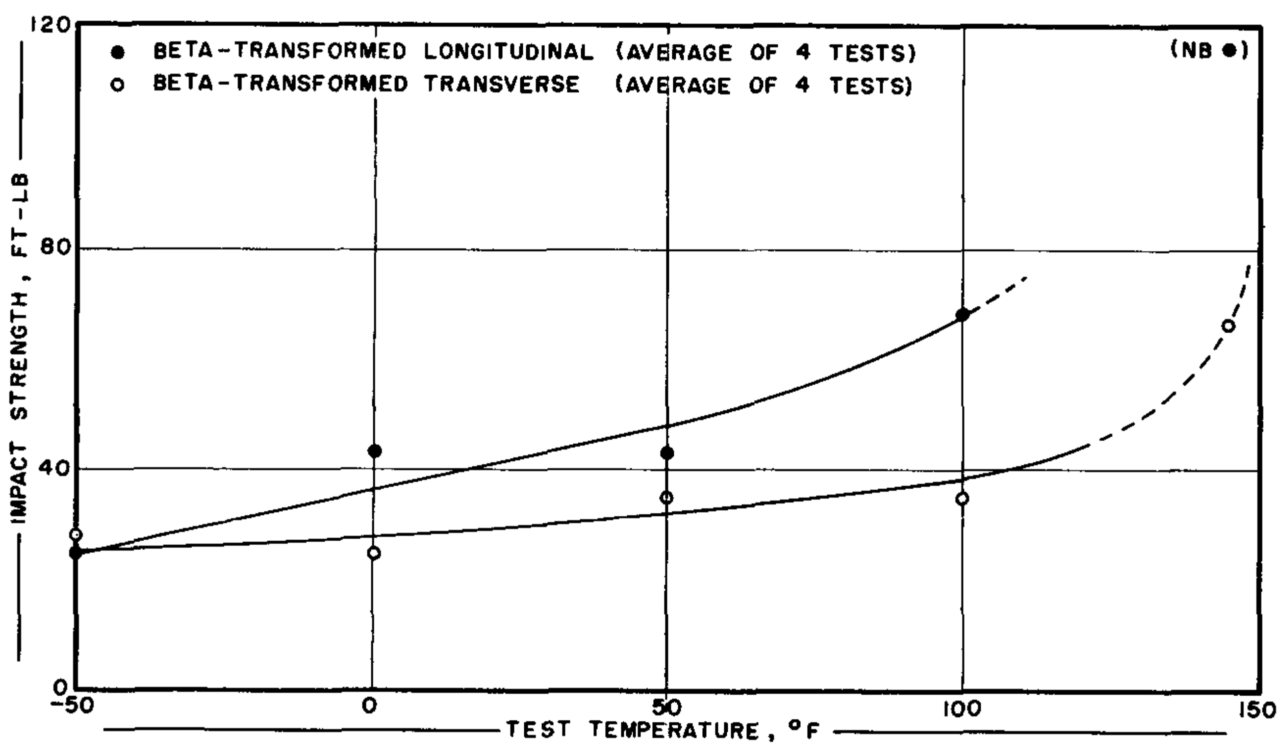
* NB-SPECIMEN DID NOT BREAK

IZOD IMPACT STRENGTH OF BETA - TRANSFORMED URANIUM

FIGURE 6



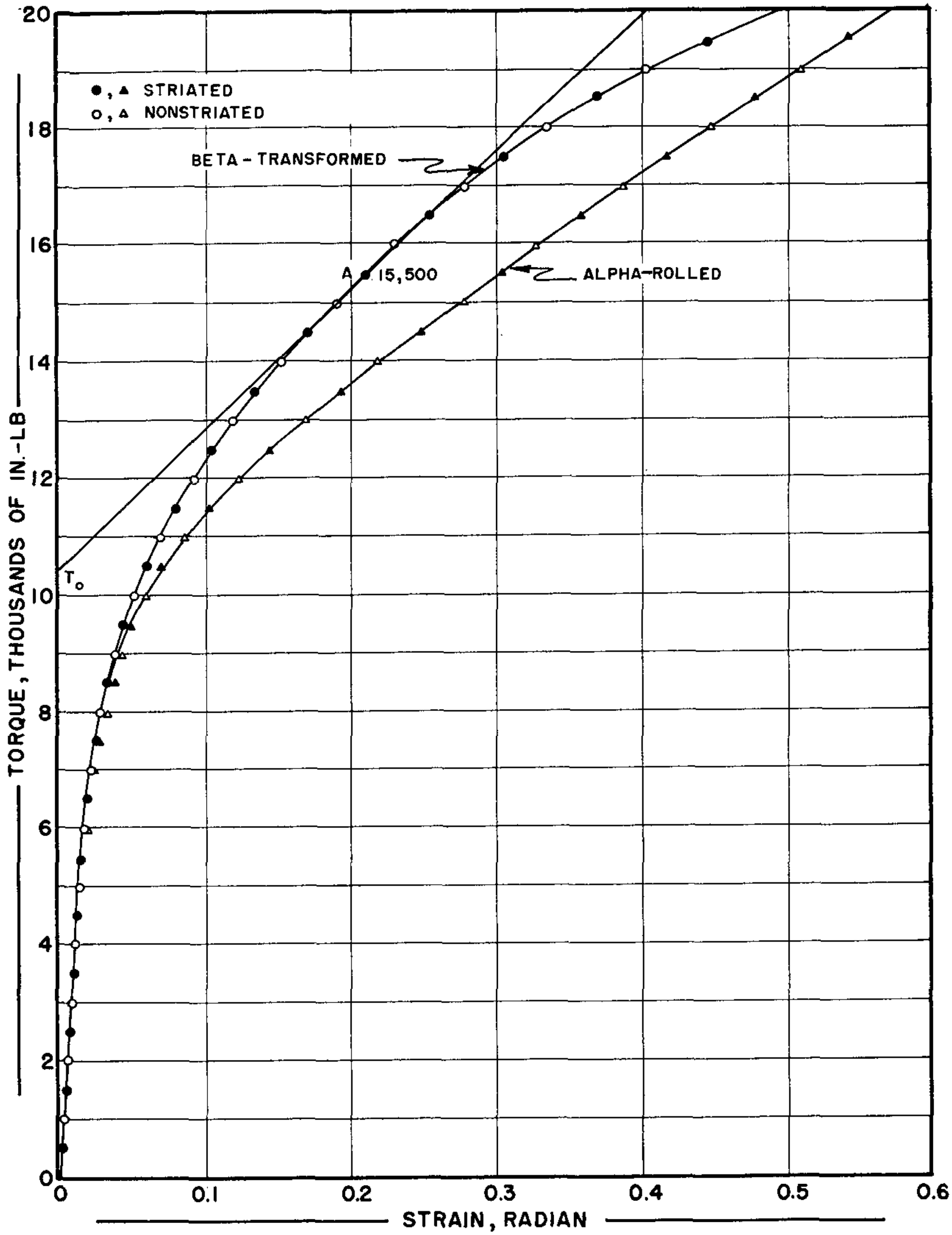
ALPHA-ROLLED URANIUM



BETA-TRANSFORMED URANIUM

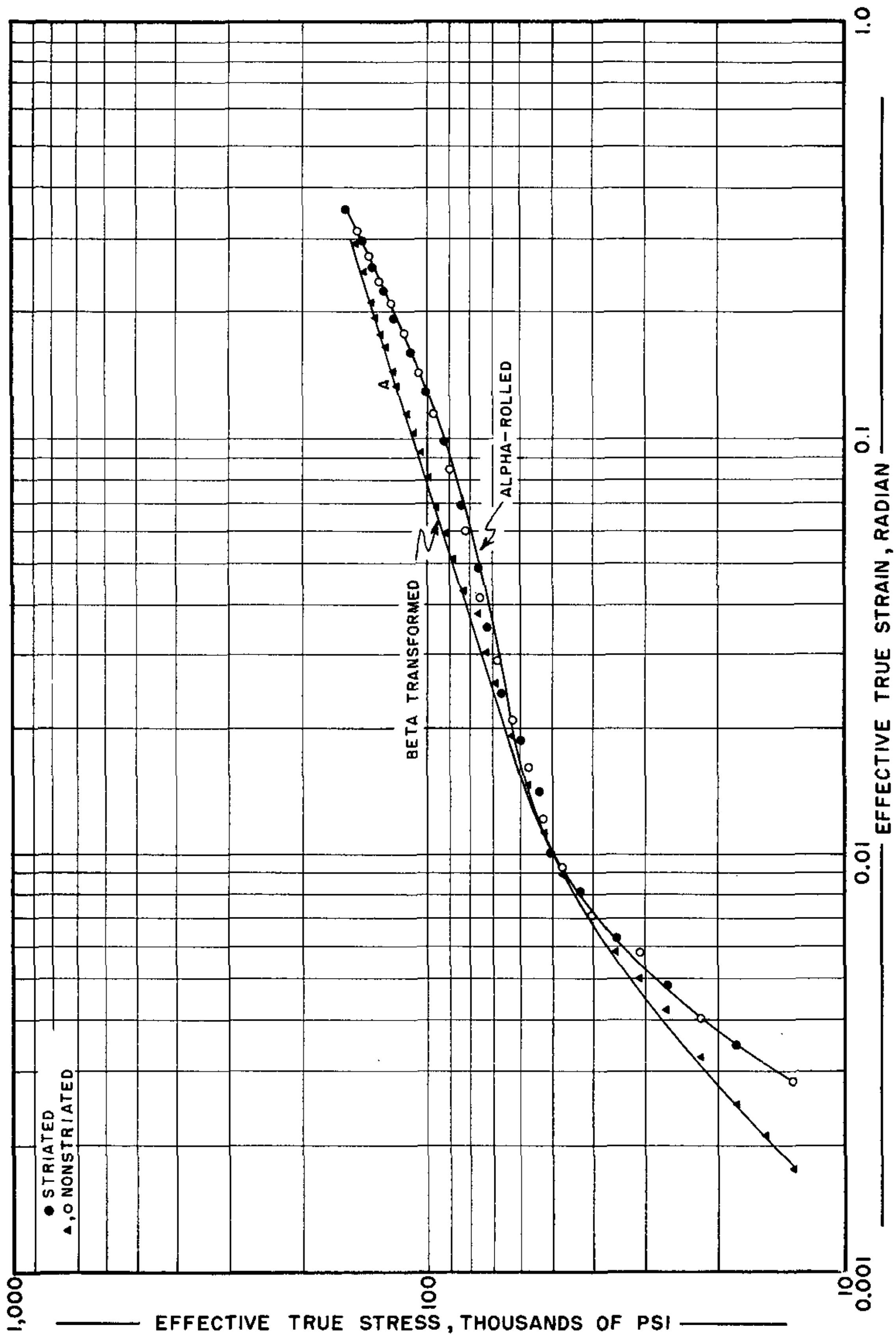
AVERAGE IMPACT STRENGTH OF URANIUM

FIGURE 7



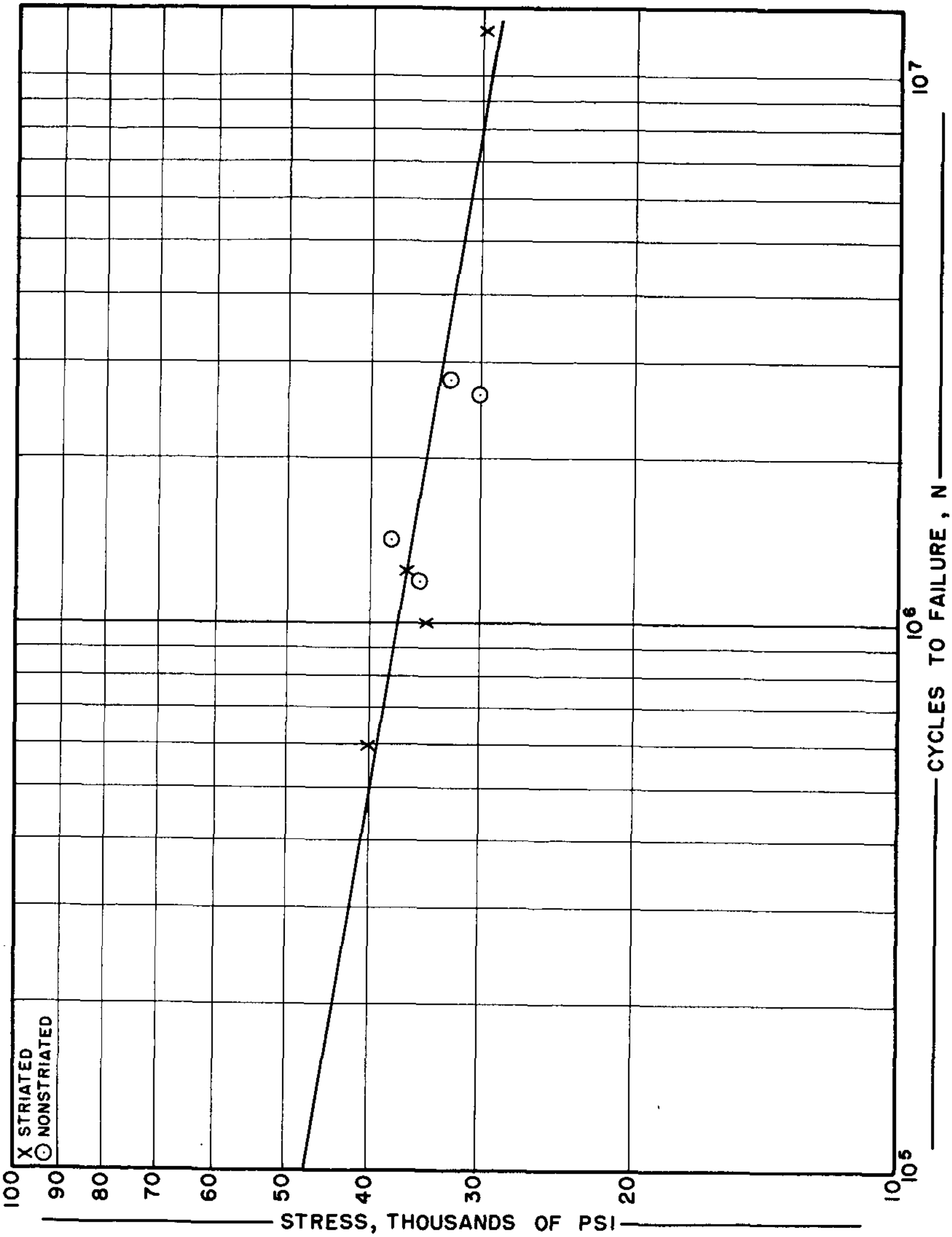
TYPICAL TORQUE - STRAIN CURVE

FIGURE 8



EFFECTIVE STRESS AND EFFECTIVE STRAIN IN TORSION

FIGURE 9



FATIGUE STRENGTH OF BETA - TRANSFORMED URANIUM

TABLE I

AVERAGE TENSILE PROPERTIES OF STRIATED AND NONSTRIATED URANIUM

Metal Quality	Heat Treatment	Orientation of Specimen in the Slug	Ultimate Tensile Strength,* psi	Reduction of Area,** per cent
nonstriated	alpha	transverse	106,000	2
striated	alpha	transverse	103,000	2
nonstriated	beta	transverse	88,000	5
striated	beta	transverse	85,000	5
nonstriated	alpha	longitudinal	122,000	17
striated	alpha	longitudinal	120,000	14
nonstriated	beta	longitudinal	91,000	8
striated	beta	longitudinal	93,000	8

* Average of four tests
** Average of two tests

TABLE II

IMPACT STRENGTH OF STRIATED AND NONSTRIATED URANIUM

Impact Strength, ft-lb

	Longitudinal Specimens, °F					Transverse Specimens, °F				
Material	-50	0	50	100	145	-50	0	50	100	145
alpha-rolled, striated	19	19	39	41	29	8	8	18	17	17
	11	57	22	24	32	10	-	9	9	12
alpha-rolled, nonstriated	22	21	35	34	72	10	24	10	34	12
	21	32	24	44	42	8	7	8	18	14
beta-transformed, striated	28	50	59	89	NB*	30	19	36	33	89
	27	37	39	NB	NB	23	33	25	37	NB
beta-transformed, nonstriated	20	27	NB	34	NB	34	20	38	35	88
	24	57	32	115	NB	25	27	40	40	44

* NB - specimen did not break

TABLE III

TORSIONAL PROPERTIES OF STRIATED AND NONSTRIATED URANIUM

Heat Treatment	Metal Quality	Torque at Fracture, in.-lb	Angle of Twist at Fracture, degrees	Angle of Twist at 20,000 in.-lb Torque, degrees	Torsional Strain-Hardening Coefficient	Strength Coefficient, psi
alpha	striated	23,000	560	360	0.26	180,000
alpha	striated			334	0.26	176,000
alpha	striated			366	0.26	172,000
beta	striated			323	0.32	219,000
beta	striated	19,850	330		0.33	226,000
beta	striated	19,750	293		0.33	230,000
alpha	nonstriated	24,100	550	320	0.26	170,000
alpha	nonstriated			261	0.27	200,000
beta	nonstriated			317	0.32	223,000
beta	nonstriated	20,025	319	312	0.32	223,000
beta	nonstriated			304	0.31	222,000
alpha	not pickled	23,450	574	345	0.24	162,000
alpha	not pickled			370	0.24	167,000
alpha	not pickled			386	0.23	161,000
alpha	pickled once	24,450	606	334	0.22	169,000
alpha	pickled once			376	0.24	166,000
alpha	pickled once			384	0.24	164,000
alpha	pickled four times	24,625	652	342	0.23	175,000
alpha	pickled four times			375	0.23	165,000
alpha	pickled four times			388	0.23	162,000
alpha	cracked	21,000	446	390	0.26	167,000
alpha	cracked	16,500	262		0.26	160,000
alpha	cracked	23,600	610	397	0.26	172,000

TABLE IV

FATIGUE PROPERTIES OF STRIATED AND NONSTRIATED URANIUM

Heat Treatment	Metal Quality	Maximum Stress, psi	Millions of Cycles to Fracture
alpha	striated	20,000	15*
alpha	striated	30,000	15*
alpha	striated	48,000	0.043
alpha	striated	39,200	0.36
alpha	striated	29,600	2.4
alpha	nonstriated	40,000	0.67
alpha	nonstriated	40,000	6.6
alpha	nonstriated	45,000	32
beta	striated	30,000	11.5
beta	striated	40,000	0.6
beta	striated	34,125	1
beta	striated	35,700	1.25
beta	nonstriated	32,500	2.8
beta	nonstriated	25,000	1.2
beta	nonstriated	38,400	1.4
beta	nonstriated	29,400	2.65

* Samples did not break