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MECHANICAL PROPERTIES OF URANIUM PLATE

by

G. R. Caskey, Jr.
Pile Materials Division

June 1959

E. I. du Pont de Nemours & Co.
Savannah River Laboratory
Aiken, South Carolina

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by

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Work done by

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ABSTRACT

Hot-rolled uranium plate exhibited a pronounced directionality in mechanical properties which was reduced but not eliminated by beta transformation. Results of tensile, bend, impact, and hardness tests made at room temperature are summarized for both hot-rolled and beta-transformed uranium plate.

Significant differences in mechanical properties existed between ten lots of uranium plate processed under similar conditions. Composition and processing data were inadequate to assign causes for the variations.

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INTRODUCTION

Mechanical tests are commonly utilized to evaluate the variability between different lots of the same material and thereby serve as a guide for control of quality. Ten lots of uranium plate were processed by Superior Steel Corporation, Carnegie, Pennsylvania, to provide cores for development of fabrication techniques for plate-type fuel elements at the Savannah River Laboratory. Evaluation of the uranium included mechanical tests of samples from each of the ten lots.

This report summarizes results of tensile, bend, impact, and hardness tests made at room temperature on samples of hot-rolled and beta-transformed uranium. The ten lots were compared by applying the control chart method of analysis of data to the ultimate tensile strength, deflection in bending, and hardness data.

SUMMARY

The mechanical properties of hot-rolled uranium plate are similar to those of uranium rod and sheet rolled at the same nominal temperature. There is a pronounced directionality in strength, ductility, and impact properties as a result of the crystalline texture and mechanical fibering developed during rolling. The mechanical fibering is produced by elongated inclusions, strings or layers of grains of varying size, and the elongated shape of the grains themselves.

Beta-transformed uranium plate has lower tensile strength and hardness and greater ductility and impact strength than the hot-rolled plate. Beta transformation reduces but does not eliminate the directionality of the mechanical properties characteristic of the as-rolled plate; however, the residual directionality does not significantly affect the performance of the metal in the reactor. The magnitudes and directions of the changes in the measured values of the mechanical properties vary for the different properties and specimen orientations. Impact strength and ductility in the transverse direction are increased by beta transformation. Tensile and yield strengths, both longitudinal and transverse, and hardness are decreased.

Statistically significant differences in tensile strength, deflection in bending, and hardness existed among the ten lots of plate for both the hot-rolled and beta-transformed conditions. These variations were probably caused by small differences in composition, process conditions, and grain size. Correlation of mechanical properties with these variables was hampered by lack of data on the carbon content of individual ingots, lack of accurate grain size determinations, and difficulties in measurement of the finishing temperature of the strip caused by variations in the oxide thickness on the rolled strip.

DISCUSSION

BACKGROUND

Rolling is the principal process for the conversion of uranium ingots to rod, plate, and sheet. Ingot breakdown, and frequently final rolling, is done in the high alpha region at temperatures of 1000 to 1200°F. Ingots or slabs are commonly preheated in a bath of molten $LiKCO_3$. The uranium may be finished at about 600°F if surface finish, gauge control, or uniformity of mechanical properties is important. The uranium is usually annealed after warm rolling to recrystallize the cold-worked structure that results from rolling at temperatures below the recrystallization temperature.

Measured values of the mechanical properties of uranium are dependent upon the processing history and the conditions of testing. Tensile strength of uranium rod decreases as the rolling temperature is increased from 600 to 1100°F.[1] The converse relation holds for elongation in tension. Uranium sheet annealed in vacuum has a greater ductility than sheet annealed in a salt bath;[2] this effect is presumed to be caused by the lower hydrogen content of the vacuum-annealed uranium. Uranium undergoes a transition from ductile to semibrittle behavior in tension in the vicinity of room temperature.[3,4] The transition temperature is sensitive to strain rate, residual strain, hydrogen content, and to a lesser extent, to heat treatment.

PROCESSING OF URANIUM PLATE

Derbies and scrap of normal uranium were melted, cast, and rolled to slabs at the Feed Materials Process Center, Fernald, Ohio. After beta transformation and surface conditioning, the slabs were rolled to strip at Superior Steel Corporation, Carnegie, Pennsylvania.[5] Rolling variables for the ten lots of strip are listed in the following table. The hot-rolled strip was 0.190 inch thick, 10 inches wide, and 50 feet long.

Sections of strip about 15 feet long were beta transformed at Atlas Steel Company, Welland, Ontario by heating in a $LiKCO_3$ salt bath for five minutes at a temperature of 1340°F. The sections were hung vertically in the salt bath. After cooling in air through the beta-to-alpha transformation, the sections were quenched in water.

Uranium plates about 3 inches wide were machined from the sections of strip. Both the machining of the plates and cutting of the sample sections for mechanical testing were done at Superior Steel Corporation.

Rolling Conditions - Superior Steel Corporation

Lot	Preheat Temperature, °F*	Number of Passes** Rough	Finish	Finishing Temperature, °F***
1	1190	5	3	1190 - 1255
2	1150	5	3	1190 - 1200
3	1150	5	3	
4	1150	5	3	1180 - 1200
5	1150	7	3	1235 - 1250
6	1130	5	3	1225 - 1270
7	1150	7	3	1260 - 1270
8	1200	7	3	--- ****
9	1200	5	3	1175 - 1290
10	1200	5	3	1185 - 1235

* Temperature of salt bath as measured with thermocouple
** Total reduction in all cases about 85%
*** Temperature of surface of strip as measured with a "Radiamatic" pyrometer
**** Response of "Radiamatic" pyrometer erratic

Density of the uranium for the ten lots of plate ranged from 18.88 to 19.04 grams/cc. Composition of the uranium was within the limits listed below.

Constituent	Analysis, ppm	Constituent	Analysis, ppm
Boron	0.1 - 0.18	Iron	20 - 150
Cadmium	0.2	Magnesium	1 - 6
Carbon	400 - 800	Manganese	4 - 12
Chloride	5 - 10	Nickel	15 - 75
Chromium	1 - 30	Nitrogen	15 - 100
Hydrogen	2 - 6	Silica	10 - 30

Metallographic examination of specimens from each lot showed typical grain sizes for both hot-rolled and beta-transformed plate. The inclusion contents were normal for reactor-grade uranium.[6]

Grain Size of Uranium Plate

Condition	Grain Size, mm	
	Average	Range
Hot-rolled	0.030	0.020 - 0.050
Beta-transformed	0.300	0.180 - 0.700

MECHANICAL TESTING

Samples for mechanical test specimens were obtained from the hot-rolled and beta-transformed strip as shown in Figure 1.

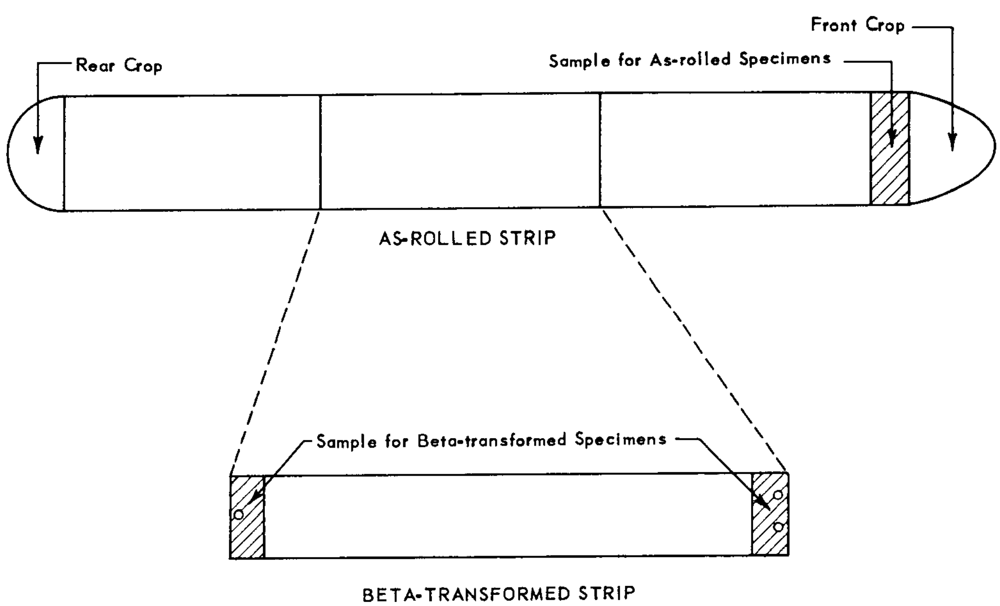

FIGURE 1 - SAMPLING PLAN FOR URANIUM STRIP

Specimens as illustrated in Figure 2 for tensile, bend, and impact tests were machined from the sample sections taken in both the longitudinal and transverse directions. Hardness tests were made in a direction normal to the plane of rolling on 1-inch-wide strips ground on one face.

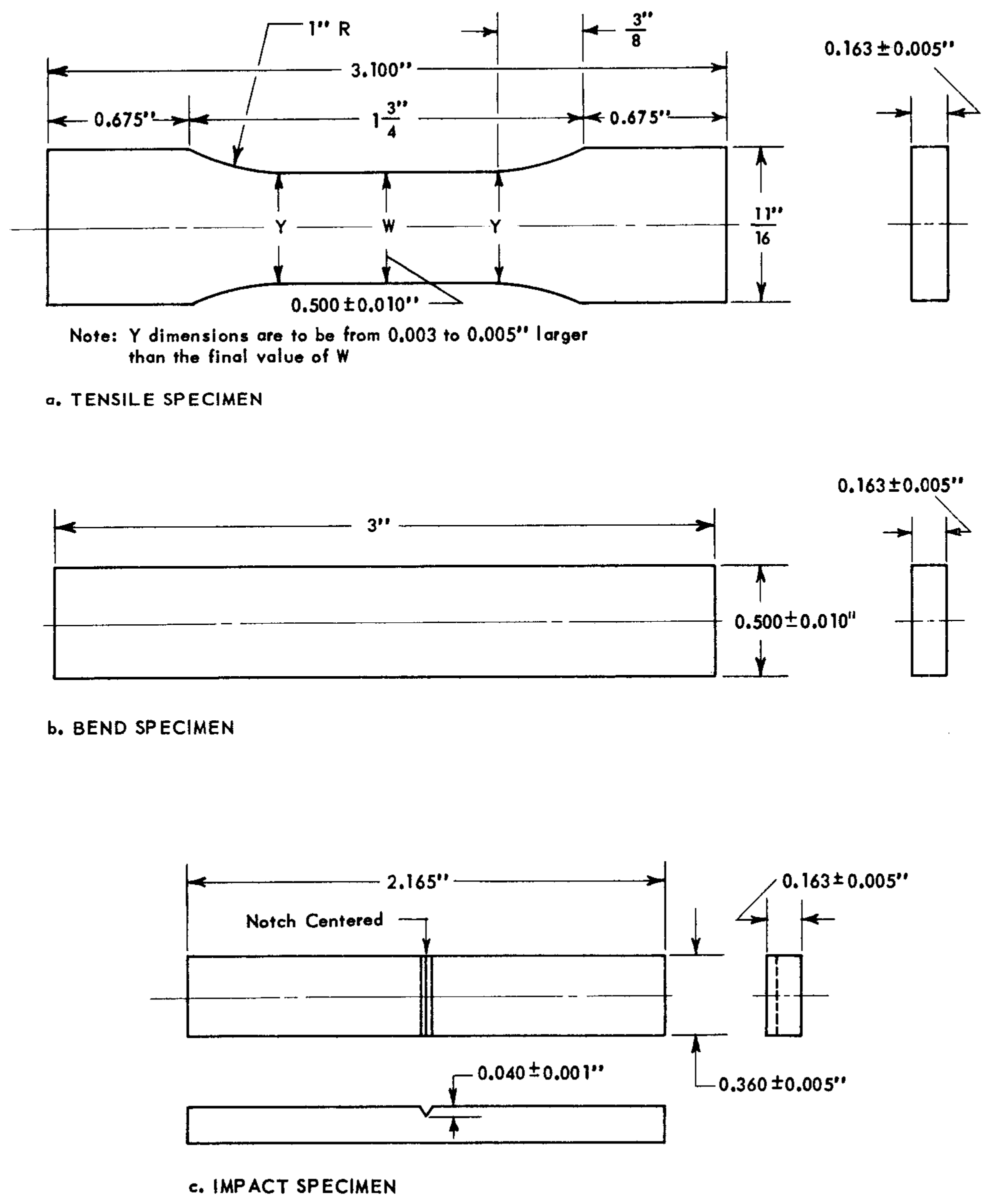

FIGURE 2 - MECHANICAL TEST SPECIMENS

Mechanical tests were made at room temperature with commercial testing equipment.

Tensile and bend tests:	Baldwin-Lima-Hamilton Universal Testing Machine 120,000-lb capacity
Impact:	Sonntag Universal Impact Machine 120 ft-lb capacity
Hardness:	Rockwell Hardness Tester - "B" scale

Conventional techniques were employed in tensile testing. The initial portion of the load-extension curve was obtained with an electric strain gauge with a 1-inch gauge length. Total elongation was measured by use of gauge marks. Test results were discarded if the specimen broke outside the gauge marks. Specimens were loaded at a rate of 6000 lb/min.

MECHANICAL PROPERTIES

Mechanical properties of hot-rolled uranium plate are about the same as for rod and sheet rolled at the same nominal temperature. As shown in the table, measured values of the mechanical properties in the longitudinal direction are generally greater than in the transverse direction.

Mechanical Properties of Hot-rolled Uranium

	Longitudinal		Transverse	
	Average	Range	Average	Range
Tensile				
Ultimate strength, psi	104,000	113,000-99,000	85,000	103,000-68,000
Yield strength, psi (0.2% offset)	44,000	58,000-36,000	66,000	83,000-41,000
Elongation, %	10.2	20-5	3.4	7-7
Bend				
Maximum load, lb	880	1,200-600	750	1,025-560
Elongation, %	6.2	17.2-1.6	3.3	4.4-1.2
Deflection, degrees	41.4	71-16	9.0	20-6
Impact				
Strength, ft-lb	1.74	2.4-0.75	1.08	1.5-0.75
Hardness*				
Rockwell "B"	96.1	103-93		

* In direction normal to plane of rolling

Directionality of properties is common in wrought metals and is caused by the crystalline texture and the mechanical fibering developed during mechanical working. The amount of directionality is influenced by the total reduction during rolling and the temperature and reduction during each pass.

Beta transformation causes a significant alteration in the mechanical properties. Impact strength and ductility are raised, and tensile strength is lowered. The large directionality in properties typical of as-rolled plate is reduced, but not entirely eliminated, as indicated in the following table. The residual effect is due principally to the mechanical fibering which is not affected by heat treatment, though there is probably a residual texture present also.

Mechanical Properties of Beta-transformed Uranium

	Longitudinal		Transverse	
	Average	Range	Average	Range
Tensile				
Ultimate strength, psi	81,000	88,000-74,000	79,000	88,000-69,000
Yield strength, psi (0.2% offset)	39,000	50,000-26,000	42,000	62,000-35,000
Elongation, %	7.0	11-2	5.7	12.5-2.1
Bend				
Maximum load, lb	770	890-680	750	890-600
Elongation, %	7.2	19-2.4	6.0	18.5-1.6
Deflection, degrees	31.2	50-18	24.0	50-10
Impact				
Strength, ft-lb	2.75	3.6-2.1	2.45	3.4-0.9
Hardness*				
Rockwell "B"	93.6	98-86		

* In direction normal to plane of rolling

Data for ultimate tensile strength, hardness, and deflection in bending were analyzed by the Control Chart Method of Analysis of Data.[7] Average and range charts were prepared according to the techniques for small samples of unequal size with no standard given. The Appendix contains a summary of the principal features of the statistical techniques that were employed and the control charts used in analysis of data. The solid horizontal lines through the charts are the weighted averages of the sample averages or ranges, $\bar{\bar{x}}$ and $\bar{R}$, respectively. The two dashed lines are the upper (UCL) and lower (LCL) control limits. These limits vary with sample size and sample average or range. Points outside the control limits are significantly different from the weighted average or range. Thus, they represent samples from a different population than the samples inside the control limits. As shown by the charts, there are significant differences in mechanical properties among the ten lots of uranium plate. The cause of the observed differences is not known, but is probably due to differences in composition and process conditions among the ten lots of plate.

Correlation of mechanical properties with composition, grain size, and process conditions was attempted. Results were inconclusive because of several factors. Carbon content of individual ingots was unknown, since samples from several ingots were batched before analysis. The inaccuracies of the usual comparison method for grain size measurement, combined with the ill-defined grain boundaries in beta-transformed uranium, did not provide grain size measurements of sufficient accuracy or precision for correlation with mechanical properties. Rolling conditions were controlled and adjusted to obtain strip of uniform thickness that was free of surface defects, and to obtain as nearly uniform a temperature as possible in the uranium during rolling. Measurement of the finishing temperature was inaccurate because variations in the oxide thickness of the rolled strip altered the emissivity of the surface, which in turn affected the indicated temperature on the "Radiamatic" pyrometer.

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APPENDIX

CONTROL CHART METHOD OF ANALYSIS OF DATA

The control charts were constructed by the procedures presented in ASTM Manual on Quality Control of Materials, Part 3, "Control Chart Method of Analysis and Presentation of Data". In the application of this procedure, the observations are divided into subgroups according to any consideration that provides a basis of classification that may be of significance. The technical basis for classification is chosen so that the variations within each subgroup may be considered to be due to chance causes only and the differences between subgroups may be considered to be due to assignable causes. The mechanical property data were classified according to the lot from which the test samples were obtained. Within each lot, the rolling conditions - total reduction, preheat temperature, number of passes, reduction per pass, and timing of the rolling - were maintained as nearly constant as possible. Changes were made, however, in the rolling conditions between lots in order to improve the uniformity of the product.

The criterion of the control chart is derived from laws of chance variations for random samples from a homogeneous material. Failure to satisfy this criterion is evidence of the presence of an assignable cause of variation. If a point lies outside of the upper or lower control limits, the property for that lot is significantly different in a statistical sense from the average for all lots. Some factor or combination of factors including composition and rolling conditions exerted a significant influence on the property in question.

Data on tensile strength, deflection in bending, and hardness were analyzed with average and range charts by the techniques for small samples of unequal size with no standard given. These three properties were chosen for analysis because the data were more extensive and considered to be more precise than the data on any of the other properties that were measured. Range rather than standard deviation was taken as a measure of dispersion of the data, since range is simpler to compute and with small samples there is little loss of effectiveness in detecting the assignable cause of variation if range rather than standard deviation is used. Where no standard values exist for the data, the techniques for "no standard given" are employed to detect assignable causes of variation among the subgroups.

The control charts for average and range for the hardness of hot-rolled plate are derived on the following pages to illustrate the method of construction of the charts. Values for the parameters d_2, A_2, D_4, and D_3 for the different sample sizes were obtained from Table II, p. 63, in ASTM Manual on Quality Control of Materials.

The relations for these factors are given below and are based on sampling from a universe with a normal distribution. For practical use in control charts they are usually satisfactory even if the universe is not normal. The factors A_2, D_3, and D_4 for calculating the control limits are functions of d_2 or d_2 and d_3. The factor d_2 is a function of the sample size n and expresses the ratio between the expected value of $\bar{R}$ for a large number of samples of size n and the true standard deviation of the universe sampled. The relations for the factors are:

$$A_2 = \frac{3}{d_2\sqrt{n}}$$

$$D_3 = 1 - 3d_3/d_2$$

$$D_4 = 1 + 3d_3/d_2$$

$$d_2 = \int_{-\infty}^{+\infty} \left[1 - (1 - \alpha_1)^n - \alpha_1^n\right] dx_1$$

$$d_3 = \left[2\int_{-\infty}^{+\infty}\int_{-\infty}^{x_1} \left[1 - \alpha_1^n - (1 - \alpha_n)^n + (\alpha_1 - \alpha_n)^n\right] dx_1 dx_n - d_2^2\right]^{1/2}$$

where

$$\alpha_1 = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{x_1} e^{-x^2/2}\,dx$$

and

$$\alpha_n = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{x_n} e^{-x^2/2}\,dx$$

In the above relations,

x_1 = smallest value in sample of size n

x_n = largest value in sample of size n

From the data on the following pages, Control Chart 3 was constructed. The range chart shows that in all but the last rolling the ranges of the hardness readings were within the anticipated limits. Six of the averages on the other hand were outside of the limits calculated from the data. In all cases, data outside of the control limits indicate that some factor in the history of that rolling or in the material is different from the other rollings.

Hardness Data - Hot-rolled Uranium Plate

Lot No.	No. of Tests	Test Values	Average $\bar{x}$	Range (R) n=2	n=4	n=5	n=6	n=8	n=13
1	13	94.5, 95.5, 94.5, 95.5, 96.0, 95.0, 95.0, 94.5, 96.0, 96.0, 96.5, 95.0	95.3						2.0
2	2	93.0, 94.0	93.5	1.0					
4	8	95.1, 94.5, 96.2, 94.2, 94.8, 95.9, 96.2, 95.6	95.3					2.0	
5	2	98.8, 98.9	98.9	0.1					
6	5	97.0, 96.2, 98.0, 97.3, 96.5	97.0			1.8			
7	6	95.7, 97.9, 95.2, 96.6, 96.6, 96.8, 95.9	96.4				2.7		
8	5	98.3, 98.8, 100.1, 101.1, 99.5	99.6			2.8			
9	6	95.9, 97.6, 98.0, 97.7	97.5				2.2		
10	4	102.4, 97.6, 100.8, 102.6	100.9		5.0				
Total	51		$\sum R_n =$	1.1	5.0	4.6	4.9	2.0	2.0

weighted average = $\bar{\bar{x}}$ = 96.8

Central Lines

For Average Chart: $\bar{\bar{x}} = 96.8$

$$\text{where } \bar{\bar{x}} = \frac{n_1\bar{x}_1 + n_2\bar{x}_2 + \cdots + n_k\bar{x}_k}{n_1 + n_2 + \cdots + n_k}$$

For Range Chart:

$n = 2 \quad \bar{R} = d_2\sigma_e = (1.128)(0.957) = 1.08$

$n = 4 \quad \bar{R} = d_2\sigma_e = (2.059)(0.957) = 1.97$

$n = 5 \quad \bar{R} = d_2\sigma_e = (2.326)(0.957) = 2.22$

$n = 6 \quad \bar{R} = d_2\sigma_e = (2.534)(0.957) = 2.42$

$n = 8 \quad \bar{R} = d_2\sigma_e = (2.847)(0.957) = 2.72$

$n = 13 \quad \bar{R} = d_2\sigma_e = (3.336)(0.957) = 3.19$

$$\text{where} \quad \sigma_e = \frac{1}{k}\sum\left(\frac{R_n}{d_2}\right)$$

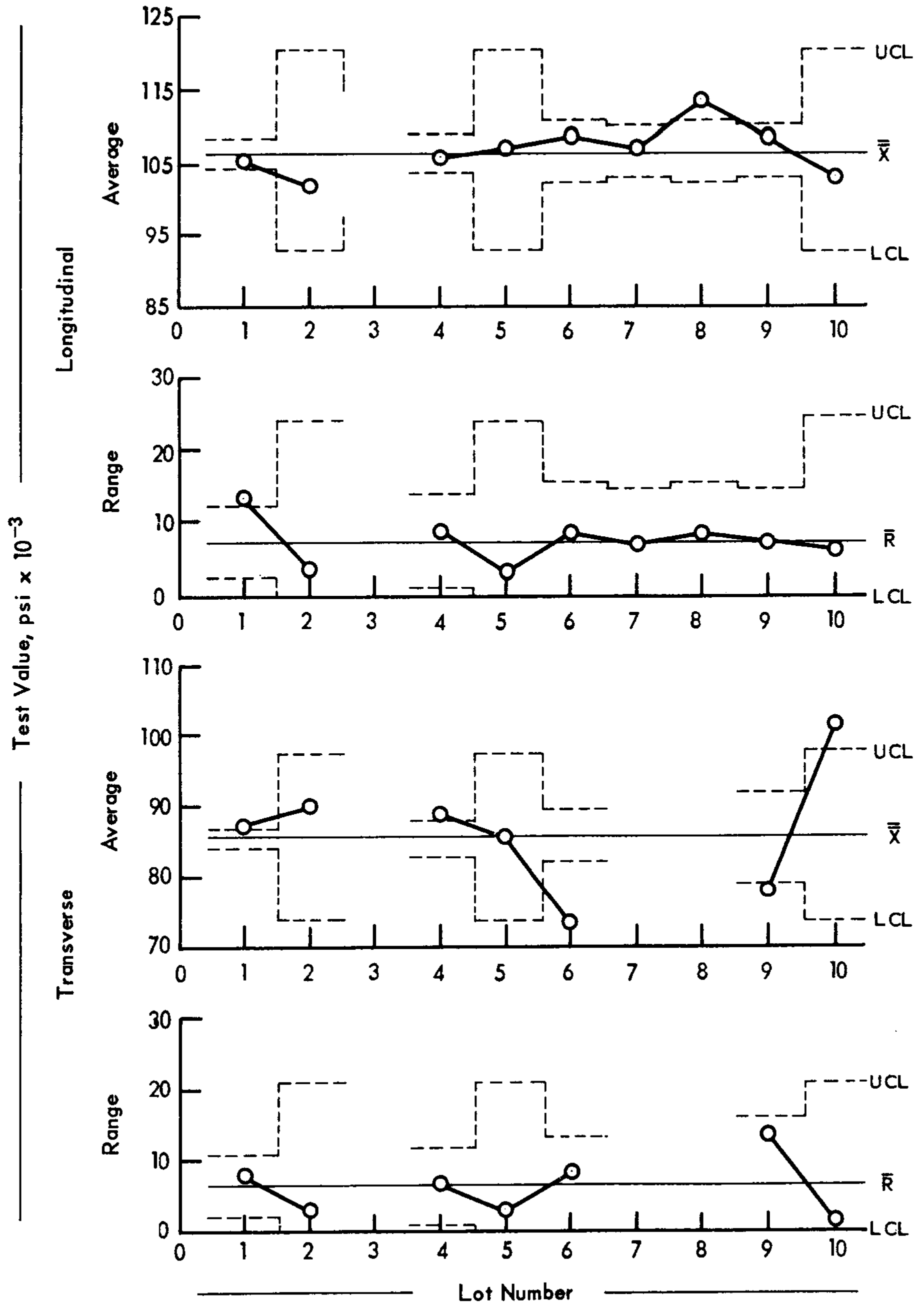
$$\sigma_e = \frac{1}{9}\left(\frac{1.1}{1.128} + \frac{5.0}{2.059} + \frac{4.6}{2.326} + \frac{4.9}{2.534} + \frac{2.0}{2.847} + \frac{2.0}{3.336}\right)$$

$$\sigma_e = 0.957$$

Control Lines

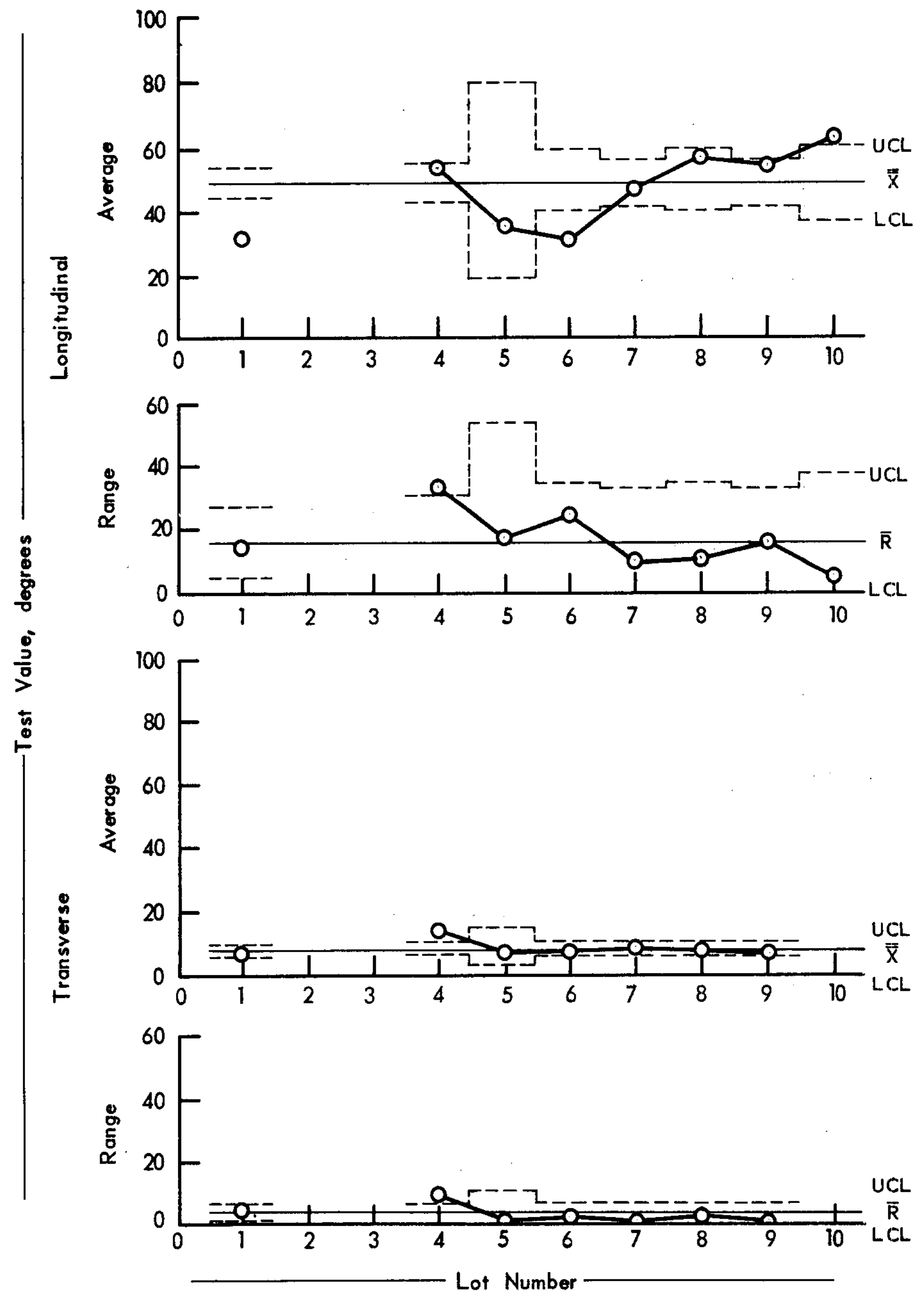
For Average Chart:	$n = 2$	$\bar{\bar{x}} \pm A_2\bar{R} = 96.8 \pm (1.880)(1.08) = 96.8 \pm 2.03$
		UCL = 98.8 LCL = 94.8
	$n = 4$	$\bar{\bar{x}} \pm A_2\bar{R} = 96.8 \pm (0.729)(1.97) = 96.8 \pm 1.44$
		UCL = 98.2 LCL = 95.4
	$n = 5$	$\bar{\bar{x}} \pm A_2\bar{R} = 96.8 \pm (0.577)(2.22) = 96.8 \pm 1.28$
		UCL = 98.1 LCL = 95.5
	$n = 6$	$\bar{\bar{x}} \pm A_2\bar{R} = 96.8 \pm (0.483)(2.42) = 96.8 \pm 1.17$
		UCL = 98.0 LCL = 95.6
	$n = 8$	$\bar{\bar{x}} \pm A_2\bar{R} = 96.8 \pm (0.373)(2.72) = 96.8 \pm 1.02$
		UCL = 97.8 LCL = 95.8
	$n = 13$	$\bar{\bar{x}} \pm A_2\bar{R} = 96.8 \pm (0.249)(3.19) = 96.8 \pm 0.79$
		UCL = 97.6 LCL = 96.0
For Range Chart:	$n = 2$	$D_4\bar{R} = (3.267)(1.08) = 3.53$
		$D_3\bar{R} = (0)(1.08) = 0$
	$n = 4$	$D_4\bar{R} = (2.282)(1.97) = 4.50$
		$D_3\bar{R} = (0)(1.97) = 0$
	$n = 5$	$D_4\bar{R} = (2.115)(2.22) = 4.69$
		$D_3\bar{R} = (0)(2.22) = 0$
	$n = 6$	$D_4\bar{R} = (2.004)(2.42) = 4.85$
		$D_3\bar{R} = (0)(2.42) = 0$
	$n = 8$	$D_4\bar{R} = (1.864)(2.72) = 5.07$
		$D_3\bar{R} = (0.136)(2.72) = 0.37$
	$n = 13$	$D_4\bar{R} = (1.642)(3.19) = 5.4$
		$D_3\bar{R} = (0.308)(3.19) = 0.98$

CONTROL CHART 1



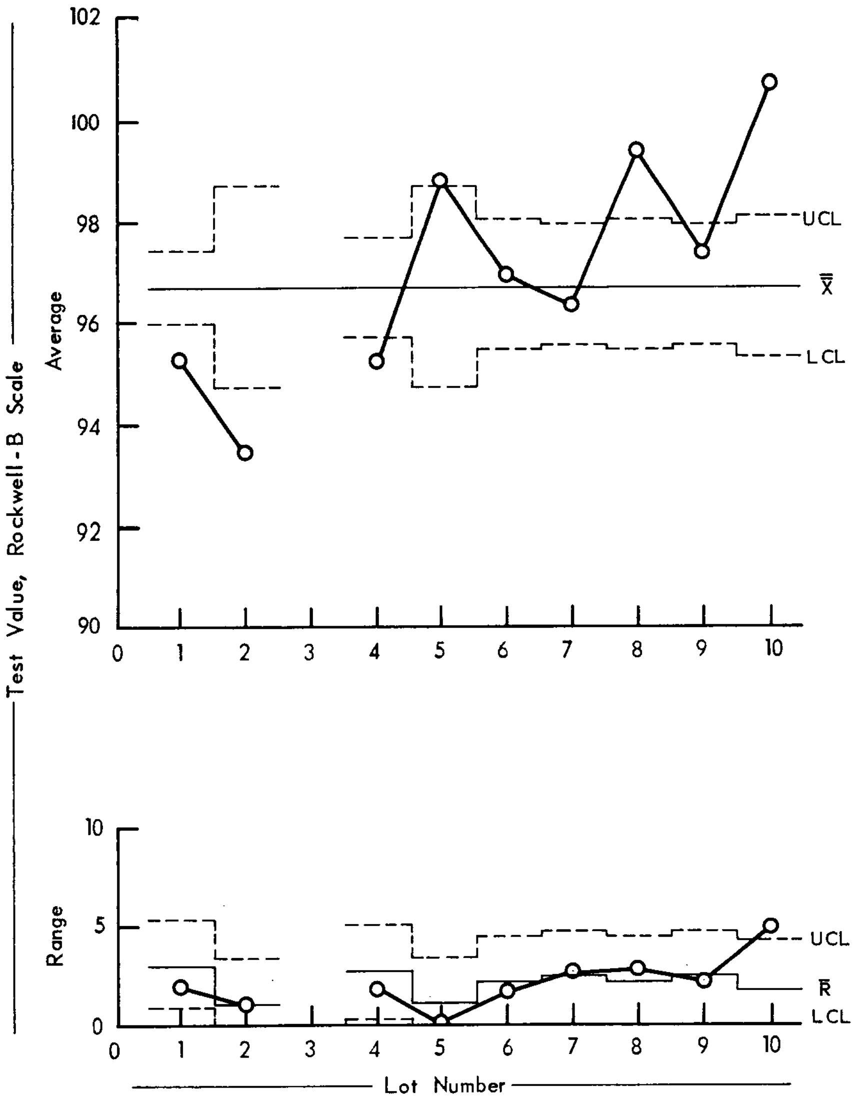
ULTIMATE TENSILE STRENGTH OF HOT-ROLLED URANIUM PLATE

CONTROL CHART 2



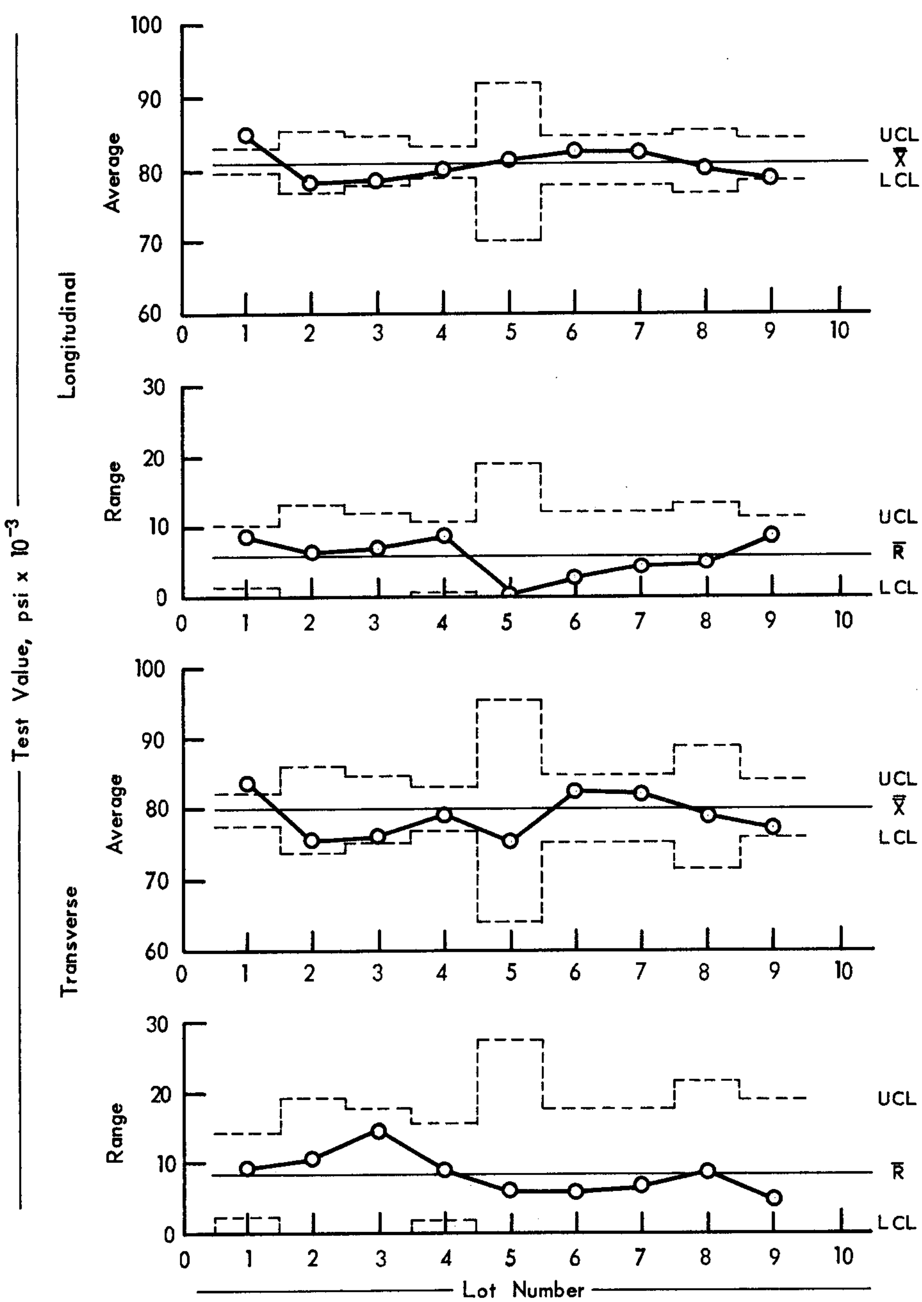
DEFLECTION IN BENDING OF HOT-ROLLED URANIUM PLATE

CONTROL CHART 3



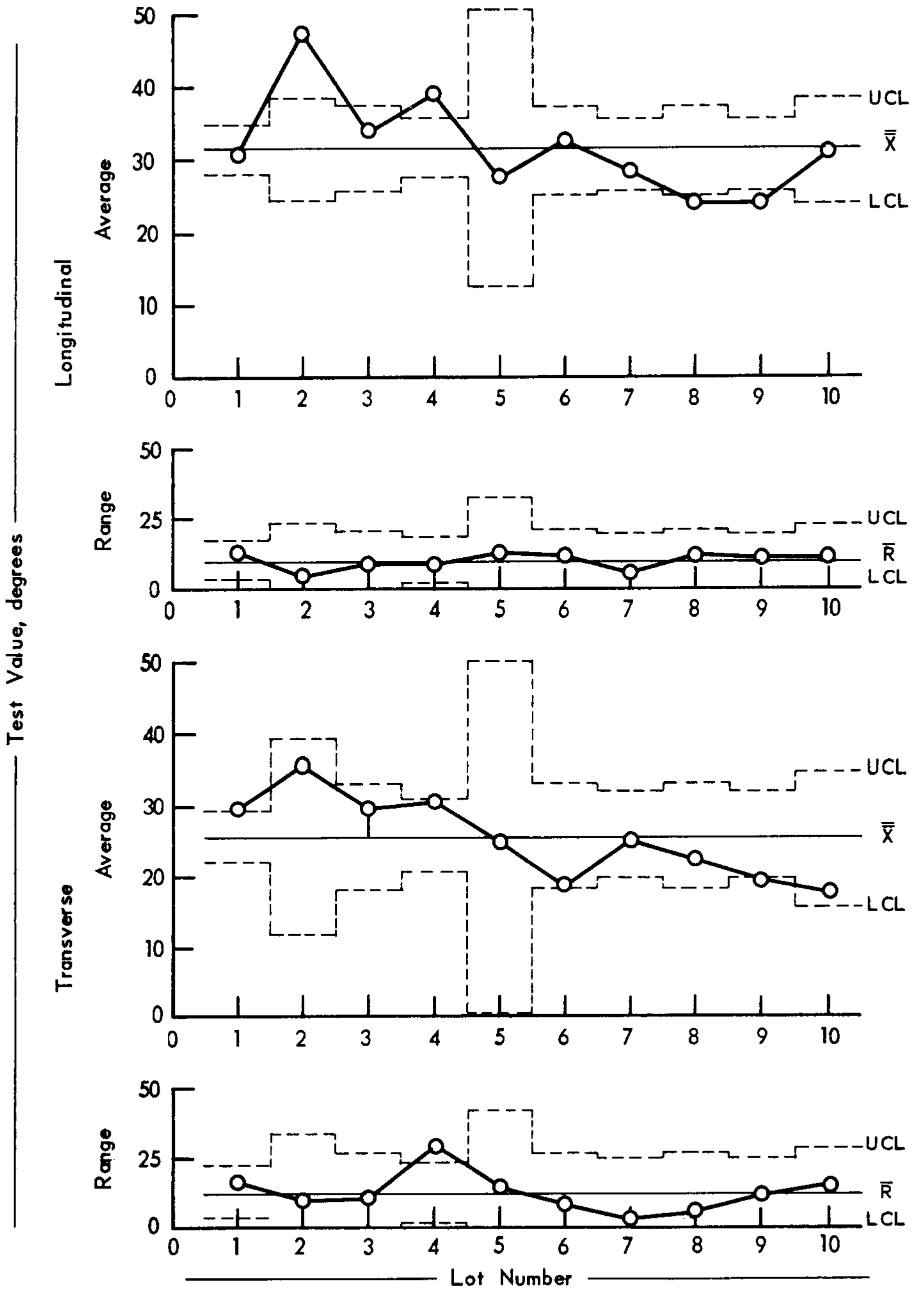
HARDNESS OF HOT-ROLLED URANIUM PLATE

CONTROL CHART 4



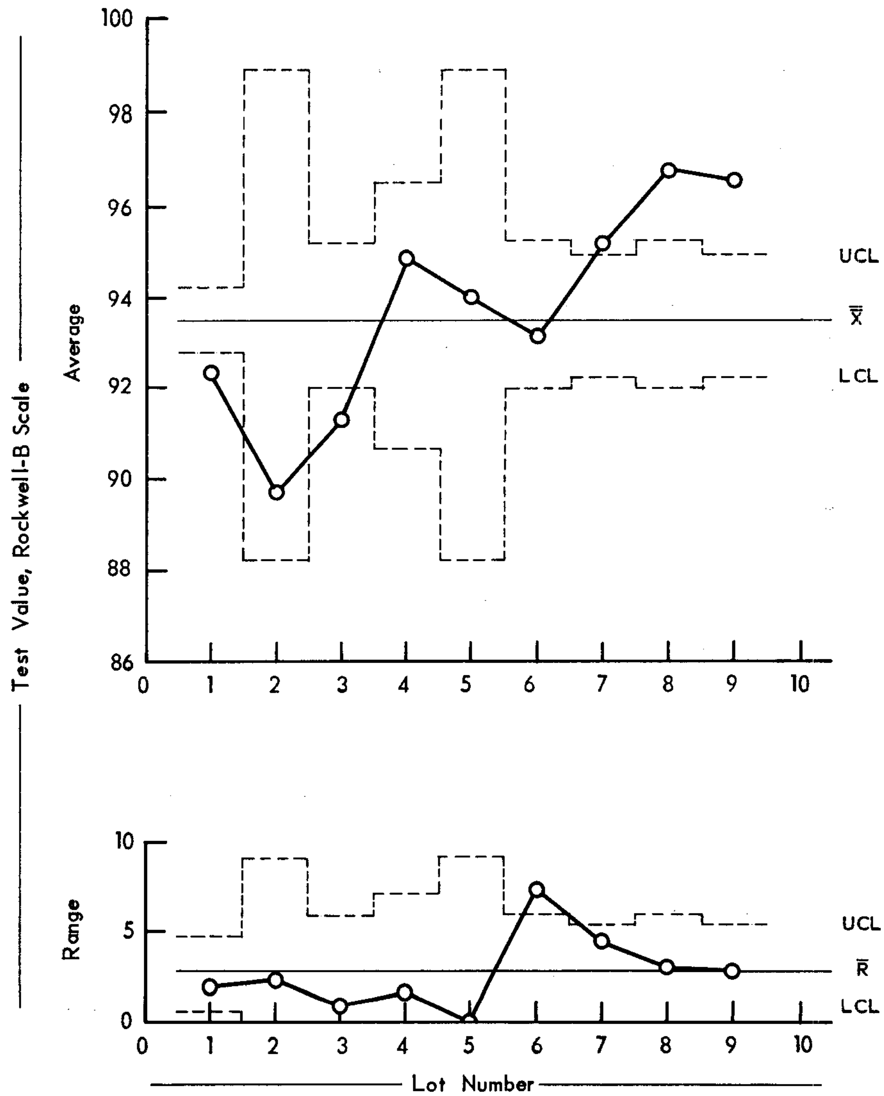
ULTIMATE TENSILE STRENGTH OF BETA-TRANSFORMED URANIUM PLATE

CONTROL CHART 5



DEFLECTION IN BENDING OF BETA-TRANSFORMED URANIUM PLATE

CONTROL CHART 6



HARDNESS OF BETA-TRANSFORMED URANIUM PLATE