ANL-6344
Metals, Ceramics, and Materials
(TID-4500, 16th Ed., Amended)
AEC Research and Development Report

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois

EFFECTS OF ROLLING AND HEAT TREATMENT ON ANISOTROPIC IRRADIATION GROWTH OF URANIUM

by

J. H. Kittel

Final Report - Metallurgy Program 6.1.15

Part of the material in this report has appeared in the following Metallurgy Division Quarterly Reports:

Report No.	Pages	Date
ANL-5423	83	October-December 1954
ANL-5439	53-57	January-March 1955

November 1961

Operated by The University of Chicago
under
Contract W-31-109-eng-38

DISCLAIMER

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EFFECTS OF ROLLING AND HEAT TREATMENT ON ANISOTROPIC IRRADIATION GROWTH OF URANIUM

by

J. H. Kittel

ABSTRACT

An investigation was made to determine the effect of rolling temperature, roll pass design, amount of reduction, and heat treatment before and after rolling on the anisotropic growth rate of uranium under irradiation. The growth rate was found to increase with decreasing rolling temperature and with increasing reduction of area at 300°C. The rate of elongation was proportional to the amount of (010) component present or, where shortening occurred, to the amount of (100) component. Oval-edge-oval roll passes resulted in somewhat higher irradiation growth rates than did round roll passes. Recrystallization after rolling effectively reduced the irradiation growth rate of uranium rolled at temperatures of 500°C and lower. Irradiation caused length shortening in uranium which was beta quenched after being round-rolled at temperatures of 400°C and above, and which was beta quenched after being oval-rolled at temperatures of 300°C and above.

INTRODUCTION

Polycrystalline alpha uranium becomes highly textured when fabricated by processes which depend upon deformation. Therefore, uranium rods fabricated by rolling, drawing, swaging, or extrusion show characteristic preferred grain orientations which may depend upon roll pass design, the degree of reduction, fabrication temperature, metal purity, and prior metallurgical history.[1-7] Alpha uranium also has an orthorhombic crystal structure and exhibits highly anisotropic physical and mechanical properties. Therefore, unusually large anisotropic effects can occur in polycrystalline alpha uranium when the effects of preferred grain orientations are added to the anisotropic properties of the alpha uranium lattice itself.

Early experiments had shown that the dimensional changes which occur in specimens of alpha uranium under thermal cycling are strongly dependent upon the amount and type of preferred orientation which may be present.[8] It was surmised that the dimensional stability of uranium under irradiation would also depend upon the grain orientation, and experiments performed in 1950 confirmed this expectation.[9] Investigations of a more extensive nature have since been performed at Argonne National Laboratory and at other sites. These studies have shown quantitatively the relationships

existing between anisotropic irradiation growth rate and fabrication procedures[4,10,11] and preferred grain orientation.[12-14]

Other investigations have been concerned with the behavior of single crystals of alpha uranium under irradiation.[15,16] These studies showed that elongation occurs in the [010] direction, shrinkage occurs in the [100] direction, and no change occurs in the [001] direction. On the basis of these results, the rate of elongation of polycrystalline uranium rods under irradiation could be expected to depend primarily upon the amount of (010) component in the axial direction. For rolled rods the amount of (010) component in the rolling direction is dependent upon rolling temperature, the amount of reduction, roll pass design, and heat treatment before and after rolling.

The present report describes an investigation which was made to determine directly the influence of these factors on anisotropic irradiation growth in polycrystalline uranium. The specimens used in the investigation were made from materials having well documented compositions and fabrication histories. Considerable use was made of surplus specimen materials from two previous investigations concerned with the influence of rolling and heat treatment on mechanical properties[17] and preferred orientation[2] in uranium. A total of 256 specimens was irradiated in the MTR and examined during the period 1954-1958. Some of the preliminary results have been previously published.[18]

SPECIMEN MATERIALS AND EXPERIMENTAL PROCEDURE

All specimens used in this investigation were made of natural reactor grade uranium. The rods from which the specimens were machined may be conveniently divided into nine groups depending upon their fabrication histories:

Group 1 - Round-Rolled
Group 2 - Oval-Rolled
Group 3 - Round-Rolled and Recrystallized
Group 4 - Oval-Rolled and Recrystallized
Group 5 - Round-Rolled and Beta Quenched
Group 6 - Oval-Rolled and Beta Quenched
Group 7 - Round-Rolled at 600°C with Subsequent Reductions at 300°C
Group 8 - Round-Rolled at 600°C and Beta Quenched with Subsequent Reductions at 300°C
Group 9 - Round-Rolled at 300°C with and without Intermediate Annealing During Rolling.

Reference 19 describes in detail the fabrication of the rods used for specimens in Groups 1 through 6. The fabrication history may be summarized as follows:

The rolling billets were vacuum-melted castings 3" square by 20" long. The castings were rolled at 600°C into 1.5" diameter rods, after which they were water quenched. They were then beta heat treated by holding at 725°C for 20 minutes and water quenching. Finish rolling was performed in either round or oval-edge-oval passes with a total reduction in each case of approximately 75 per cent. The roll pass designs and dimensions are shown in Figures 1 and 2. Each rod was preheated 15 minutes in the heating medium (oil or salt baths depending upon temperature) and then rolled one direction only, with intermediate soaking for 3 minutes after each pass. The rolling temperatures as stated in the present report are in reality those of the preheat baths. Measurements of actual rod temperatures during rolling, although of doubtful accuracy, indicated that at the higher rolling temperatures the rod temperatures were lower than the preheat bath temperatures. The fabrication of the 300°C rolled material in Group 5 was done similarly and is described in detail in Reference 19.

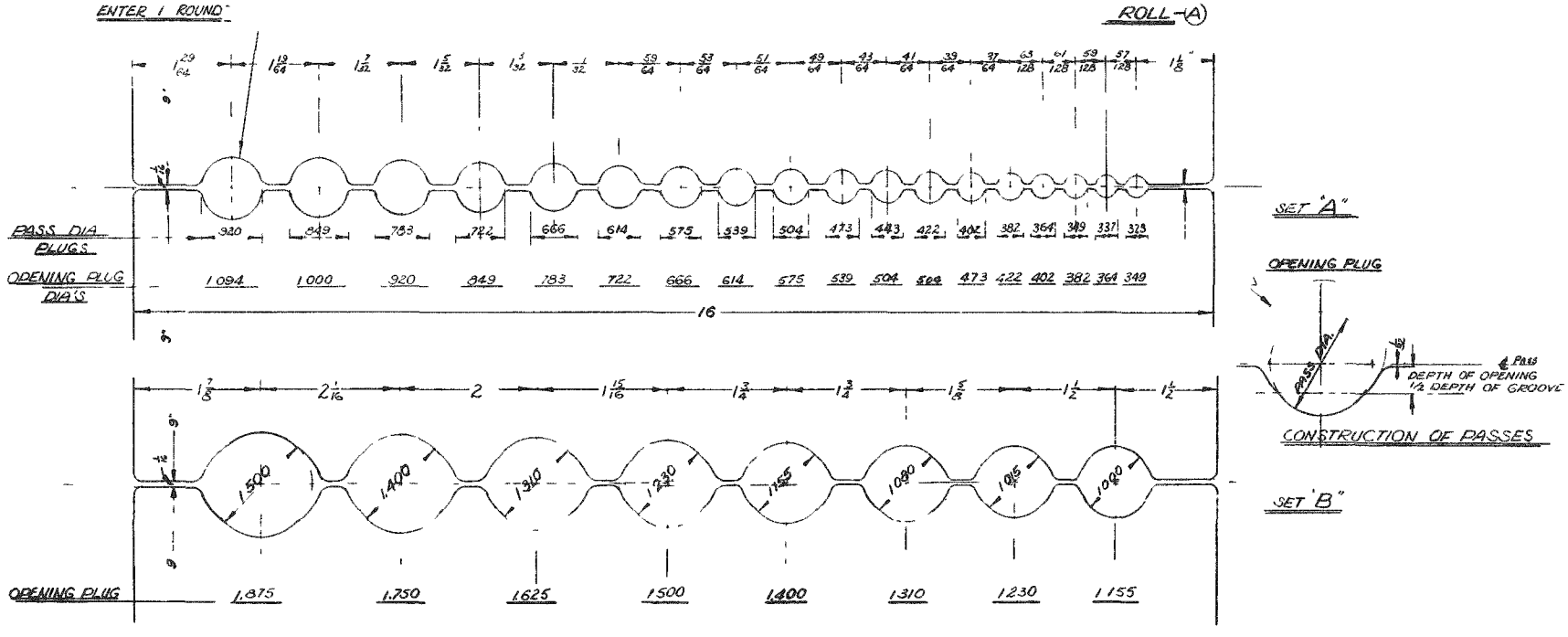
The annealing heat treatments used to recrystallize the materials in Groups 3 and 4 are also described in a separate report.[17] Most of the rods were annealed for 2 hours at selected temperatures between 575° and 630°C. The purpose of the annealing treatments was to produce the same final grain size in each rod regardless of rolling temperature. This was successful in those rods rolled below 640°C. In these rods the grain size ranged from 0.025 to 0.035 mm diameter, whereas the 640°C rolled material had a grain size of 0.065 mm.

The beta quenching heat treatment used in Groups 5 and 6 was done as a part of the present investigation. The specimens were heated in an argon-filled tube to 725°C, held for 15 minutes, and quenched directly from the tube into water.

The fabrication of the rods used in Groups 7 and 8 is described in detail in Reference 2. The fabrication history may be summarized as follows:

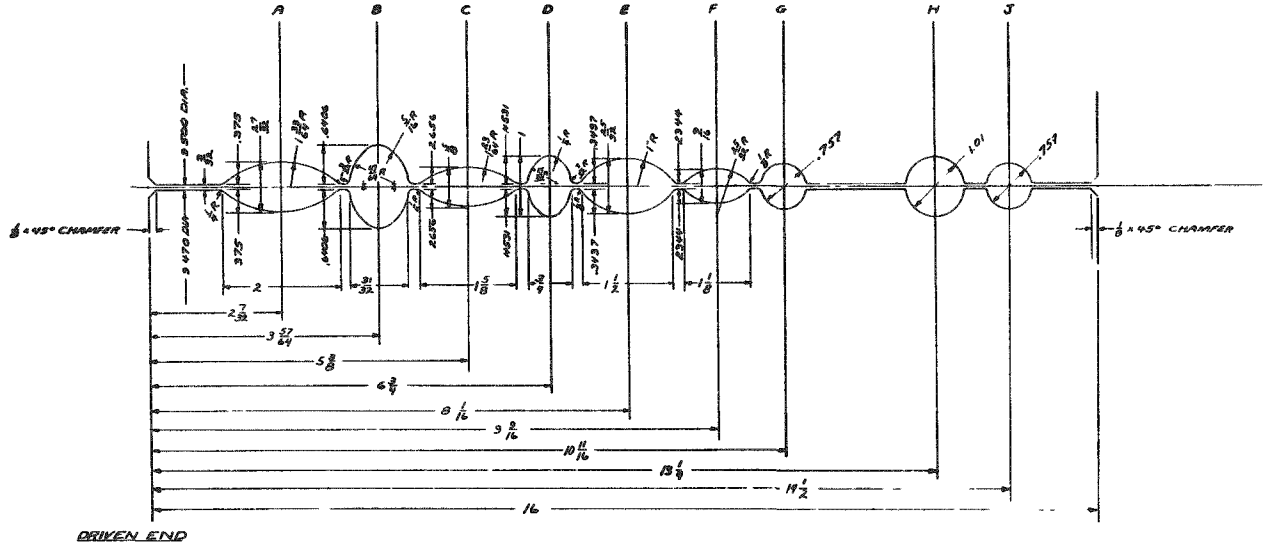
A 3" square cast billet was rolled at 600°C to a 2" square. It was then beta quenched and rolled at 600°C to a 1" diameter round. Part of this round rod was then given subsequent reductions by rolling at 300°C; this material was used in Group 7. An additional part of the round rod was beta quenched and annealed for two hours at 550°C before being given subsequent reductions at 300°C; this material was used in Group 8.

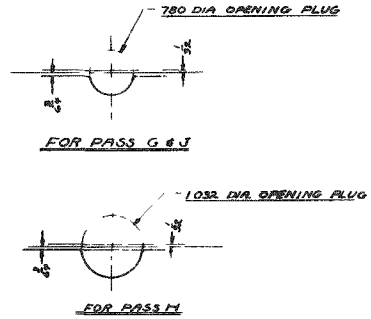
The material used for the Group 9 specimens was made available from an investigation on the preparation of single crystals of alpha uranium.[20] Rods with two different fabrication histories were used. One rod was reduced 75 per cent in area by rolling at 300°C. The other rod was also reduced by rolling at 300°C, but was recrystallized by annealing at temperatures from 525° to 600°C between each pass in order to reduce banding and to obtain a more uniform grain size. The last reduction in area at 300°C was 47.5 per cent.



106-2544

Figure 1. Roll Passes Used for Round-Rolled Material.





ROLLING SCHEDULE

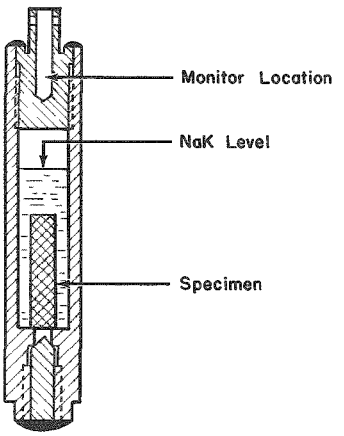
ENTER 1½" ϕ @ 1.7671 lbs/ft

PASS	AREA	RED	PASS	AREA	RED
A	1.27 in²	28%	A	1.27 in²	28%
B	1.09 in²	18%	B	1.09 in²	18%
C	.78 in²	25%	E	.91 in²	12.6%
D	.61 in²	21.8%	H	.785 in²	13.6%
F	.51 in²	16.5%			
J	.4418 in²	13%			

106-2543

Figure 2. Roll Passes Used for Oval-Rolled Material.

Since the property of greatest interest was the dimensional stability of the specimens under irradiation, they were irradiated under conditions where they were free of physical restraint. This was accomplished by using loosely fitting aluminum or zirconium capsules containing NaK for heat transfer. A typical capsule is shown in Figure 3.



106-1760

Figure 3

Assembled Irradiation Capsule (1/2" Diameter).

Each capsule contained an aluminum-0.5 w/o cobalt alloy flux monitor. The activation of the monitor provided data for calculations of fuel burnups and irradiation temperatures. Appropriate corrections were made for such factors as resonance activation in the cobalt and for plutonium production and fission in the fuel specimens. Indicated burnup values from the flux monitors were checked regularly against actual burnup determinations by radiochemical analyses of Cs^{137}. The irradiation technique had been developed earlier for MTR conditions and has been described previously.(10)

Where the condition of the specimen permitted, dimensional measurements on irradiated specimens were made by micrometers. Dimensional determinations on distorted specimens were made by measuring photographs containing a length standard along with the specimen. Hardness measurements were made on the Rockwell A scale. Many of the specimens were too distorted after irradiation for meaningful hardness measurements on the original outer surface.

RESULTS AND DISCUSSION

The irradiation conditions and changes observed in each specimen are shown in Tables I through IX. The nine tables of data correlate respectively with the nine groups of specimen materials described in the previous section. The tables show for each specimen a growth coefficient, G_i. Derivation of this coefficient, which is the average rate of irradiation growth, has been described previously.(10) For small elongations

$$G_i \approx \frac{\%\ \text{Length Change}}{\text{a/o Burnup}}$$

Burnups in the specimens ranged from 0.0020 to 0.76 a/o. Maximum (center of fuel) irradiation temperatures ranged from 50° to 460°C. Most of the specimens irradiated above 400°C were swollen and could not be removed from their irradiation capsules.

Table I

EFFECT OF IRRADIATION ON ROUND-ROLLED SPECIMENS

Spec. No.	Original Rod No.	Rolling Temp., °C	Burnup, a/o	Irrad. Temp., °C		Length Change, %	G_i microin./in. ppm burnup	Diameter Change, %	Weight Change, mg.	Hardness Change, R_A
				Surface	Center					
BE-1-3	34D-695-6	300	0.0021	45	50	1.6	760	-0.56	1.9	1.9
BE-2-3	34D-695-6	300	0.0022	45	50	1.7	770	-0.84	0.8	1.0
BE-14-1	34D-695-6	300	0.0038	50	60	3.4	880	-1.5	1.3	-0.8
BE-13-1	34D-695-6	300	0.0040	50	60	3.3	810	-0.80	-4.3	0
BE-3-3	34D-695-6	300	0.011	70	90	9.1	790	-4.1	1.6	2.3
BE-4-3	34D-695-6	300	0.015	85	120	13.1	820	-5.8	2.1	3.3
BE-15-1	34D-695-6	300	0.023	100	150	19.3	770	-8.1	1.0	4.0
BE-16-1	34D-695-6	300	0.035	150	220	34.4	840	-12.8	-1.6	1.1
AA-127	34D-695-6	300	0.083	65	85	(a)	-	-25	1.5	(a)
AA-128	34D-695-6	300	0.18	100	150	(a)	-	-30	(b)	(a)
AA-129	34D-695-6	300	0.27	140	230	(a)	-	(a)	(b)	(a)
AA-130	34D-695-6	300	0.37	190	320	(a)	-	(a)	(b)	(a)
						Average G_i Value = 805				
BE-5-2	34D-708-5	400	0.0027	50	55	1.6	590	-0.44	2.3	1.9
BE-6-2	34D-708-5	400	0.0028	50	55	1.4	500	-0.88	2.2	2.0
BE-13-3	34D-708-5	400	0.0038	50	60	1.9	500	-0.84	1.1	2.9
BE-14-3	34D-708-5	400	0.0039	50	60	2.4	610	-1.4	1.1	1.0
BE-7-2	34D-708-5	400	0.017	90	120	9.2	520	-3.9	1.5	3.1
BE-8-2	34D-708-5	400	0.022	110	160	14.1	600	-5.9	1.8	3.5
BE-15-3	34D-708-5	400	0.023	100	140	12.0	490	-4.9	1.0	3.0
AA-131	34D-708-5	400	0.032	100	150	16.4	480	-6.3	0.6	2.9
BE-16-3	34D-708-5	400	0.035	150	220	22.8	590	-8.3	1.3	3.8
AA-132	34D-708-5	400	0.10	110	170	(a)	-	-25	8.2	(a)
AA-134	34D-708-5	400	0.13	70	100	(a)	-	-28	1.5	(a)
AA-133	34D-708-5	400	0.14	100	150	(a)	-	-27	-460.7	(a)
						Average G_i Value = 540				
BE-9-3	34D-706-7	500	0.0027	50	55	0.41	150	-0.28	1.9	0.3
BE-10-3	34D-706-7	500	0.0031	50	55	0.65	210	-0.12	2.8	2.9
BE-21-1	34D-706-7	500	0.0050	55	65	0.93	190	-0.68	1.7	3.8
BE-22-1	34D-706-7	500	0.0051	55	65	0.95	190	-0.36	1.8	5.3
BE-11-3	34D-706-7	500	0.015	80	110	2.8	180	-1.4	1.2	6.3
BE-23-1	34D-706-7	500	0.025	110	160	5.1	200	-2.4	1.8	6.7
BE-12-3	34D-706-7	500	0.029	130	190	6.5	220	-2.4	1.9	5.7
BE-24-1	34D-706-7	500	0.041	170	250	9.2	210	-3.2	1.6	4.7
AA-135	34D-706-7	500	0.048	130	200	13.3	260	-6.4	0	7.3
AA-136	34D-706-7	500	0.17	140	230	81.3	350	-28	1.5	(a)
AA-137	34D-706-7	500	0.28	140	230	(c)	-	(c)	(c)	(c)
AA-138	34D-706-7	500	0.39	140	230	(c)	-	(c)	(c)	(c)
						Average G_i Value = 215				
BE-25-2	34D-706-1	600	0.0041	50	60	-0.040	-10	-0.16	1.0	5.6
BE-26-2	34D-706-1	600	0.0047	55	65	-0.067	-14	-1.2	0.9	5.8
BE-27-2	34D-706-1	600	0.018	90	120	0.053	2.9	-0.16	1.5	7.6
BE-28-2	34D-706-1	600	0.040	160	250	0.013	0.3	0.64	1.2	7.5
AA-163	34D-706-1	600	0.056	130	230	0.23	4.1	0.60	-2.2	6.9
AA-164	34D-706-1	600	0.18	160	250	2.8	15	3.2	1.5	16.0
AA-165	34D-706-1	600	0.27	150	240	6.0	22	0.7	3.4	15.5
AA-166	34D-706-1	600	0.57	180	290	(c)	-	(c)	(c)	(c)
						Average G_i Value = 2.9				
BE-33-1	34D-695-3	640	0.0051	55	65	-0.093	-18	-0.08	1.0	8.3
BE-34-1	34D-695-3	640	0.0057	55	70	-0.21	-37	-0.28	-0.1	0.7
BE-35-1	34D-695-3	640	0.021	100	140	-0.69	-33	0.60	0.9	7.7
BE-31-3	34D-695-3	640	0.027	100	160	-1.1	-41	0.20	1.2	7.5
BE-36-1	34D-695-3	640	0.041	170	250	-0.94	-23	1.8	0.1	7.7
BE-32-3	34D-695-3	640	0.042	170	260	-1.0	-24	1.5	1.9	8.2
AA-139	34D-695-3	640	0.076	180	290	-1.6	-21	2.7	0.4	7.8
AA-141	34D-695-3	640	0.21	180	290	-12.4	-61	13.5	0.6	(a)
AA-142	34D-695-3	640	0.40	190	320	-6.7	-17	9.0	0.7	(a)
						Average G_i Value = -31				

(a) Specimen too distorted for measurement. (b) Measurement not obtained. (c) Specimen could not be removed from irradiation capsule for measurement.

Table II

EFFECT OF IRRADIATION ON OVAL-ROLLED SPECIMENS

Spec. No.	Original Rod No.	Rolling Temp., °C	Burnup, a/o	Irrad. Temp., °C		Length Change, %	G_i microin./in. ppm burnup	Diameter Change, %	Weight Change, mg.	Hardness Change, R_A
				Surface	Center					
BE-2-1	44D-681-5	300	0.0020	45	50	1.9	940	-0.16	0.9	3.0
BE-1-1	44D-681-5	300	0.0020	45	50	1.8	890	-0.80	1.3	4.3
BE-13-2	44D-681-5	300	0.0035	50	60	3.2	900	-1.5	1.5	3.2
BE-14-2	44D-681-5	300	0.0039	50	60	2.6	660	-0.76	1.2	4.3
BE-3-1	44D-681-5	300	0.011	70	90	9.7	840	-4.2	(b)	2.7
BE-4-1	44D-681-5	300	0.014	85	120	14.0	940	-5.7	1.4	2.4
BE-15-2	44D-681-5	300	0.023	100	140	17.3	690	-6.9	1.3	-0.8
AA-167	44D-681-5	300	0.031	100	150	28.6	810	-9.4	-0.8	1.3
BE-16-2	44D-681-5	300	0.035	150	220	29.7	740	-8.4	1.2	-0.9
AA-168	44D-681-5	300	0.090	100	150	(a)	-	(a)	21.5	(a)
AA-169	44D-681-5	300	0.16	100	160	(c)	-	(c)	(c)	(c)
AA-170	44D-681-5	300	0.16	80	120	(c)	-	(c)	(c)	(c)
						Average G_i Value = 825				
BE-5-1		400	0.0027	50	55					
BE-6-1	44D-680-3	400	0.0029	50	55	1.9	650	-1.2	1.9	4.7
BE-17-2	44D-680-3	400	0.0037	50	60	2.2	590	-1.0	1.2	4.8
BE-18-2	44D-680-3	400	0.0039	50	60	2.5	630	-1.2	1.2	3.6
AA-171	44D-680-3	400	0.0097	55	70	6.2	620	-2.4	0.7	5.3
BE-7-1	44D-680-3	400	0.017	85	120	10.8	600	-4.2	1.9	2.6
BE-19-2	44D-680-3	400	0.017	90	120	11.1	620	-5.6	1.0	2.3
BE-8-1	44D-680-3	400	0.023	110	160	15.8	640	-6.8	1.9	4.5
AA-172	44D-680-3	400	0.028	55	70	15.4	510	-5.5	1.5	4.5
BE-20-2	44D-680-3	400	0.039	160	240	22.4	520	-5.5	1.4	1.5
AA-173	44D-680-3	400	0.044	55	70	28.1	560	-10.2	2.4	0.3
AA-174	44D-680-3	400	0.16	80	120	(a)	-	(a)	-41.9	(a)
						Average G_i Value = 595				
BE-9-1	44D-680-5	500	0.0027	50	55	0.63	230	-0.76	1.2	2.4
BE-10-1	44D-680-5	500	0.0029	50	55	0.96	330	0.48	2.5	3.6
BE-17-1	44D-680-5	500	0.0036	50	60	1.1	300	-0.84	2.2	4.9
BE-18-1	44D-680-5	500	0.0041	50	60	1.4	340	-0.92	1.8	3.3
AA-175	44D-680-5	500	0.012	60	80	4.1	330	-1.9	2.0	4.9
BE-11-1	44D-680-5	500	0.015	80	110	4.1	270	-2.0	1.2	3.5
BE-19-1	44D-680-5	500	0.017	90	120	5.4	310	-1.5	-8.4	7.9
BE-12-1	44D-680-5	500	0.029	130	190	11.1	360	-4.8	1.6	6.5
AA-176	44D-680-5	500	0.035	60	80	10.5	290	-4.8	1.2	5.8
BE-20-1	44D-680-5	500	0.040	160	240	16.4	380	-6.7	1.6	2.8
AA-177	44D-680-5	500	0.061	60	80	18.9	280	-7.6	0.3	4.5
AA-178	44D-680-5	500	0.14	75	110	72	390	-26	1.2	3.4
						Average G_i Value = 320				
BE-25-1	44D-677-4	600	0.0040	50	60	0.39	97	-0.32	1.7	5.8
BE-26-1	44D-677-4	600	0.0048	55	65	0.55	110	-0.52	1.4	5.0
BE 22-2	44D-677-4	600	0.0050	55	65	0.43	86	-0.20	1.1	7.5
BE-21-2	44D-677-4	600	0.0052	55	65	0.44	85	-0.44	1.4	6.1
BE-27-1	44D-677-4	600	0.018	90	130	1.7	94	-0.88	1.6	4.6
BE-23-2	44D-677-4	600	0.025	110	160	2.4	95	-1.2	1.4	5.2
BE-28-1	44D-677-4	600	0.041	170	250	4.6	110	-1.7	1.6	7.4
BE-24-2	44D-677-4	600	0.041	170	250	4.1	98	-1.6	1.4	7.3
AA-179	44D-677-4	600	0.057	140	230	4.8	82	-2.0	0.6	7.9
AA-180	44D-677-4	600	0.15	140	230	21.7	120	-7.3	0.5	11.8
AA-182	44D-677-4	600	0.30	160	250	46.1	130	-18.1	1.5	11.5
						Average G_i Value = 100				
BE-21-3	44D-677-7	640	0.0050	55	65	0.093	19	-0.16	1.2	5.1
BE-22-3	44D-677-7	640	0.0054	55	65	0.25	46	-0.16	1.2	7.4
BE-29-1	44D-677-7	640	0.0058	55	70	0.16	28	-0.04	1.5	4.4
BE-30-1	44D-677-7	640	0.0062	60	70	0.20	32	-0.28	1.3	7.0
BE-31-3	44D-677-7	640	0.027	110	160	1.00	37	-0.52	1.4	6.5
BE-23-3	44D-677-7	640	0.027	110	160	0.67	25	-0.08	1.1	6.3
BE-24-3	44D-677-7	640	0.040	160	240	0.55	14	-0.20	1.1	7.0
BE-32-1	44D-677-7	640	0.043	170	260	1.96	45	-0.68	1.3	7.4
AA-183	44D-677-7	640	0.085	200	330	3.01	35	0.39	0.5	7.2
AA-184	44D-677-7	640	0.35	260	430	55.5	130	5.5	25.4	6.8
AA-185	44D-677-7	640	0.37	230	380	(c)	-	(c)	(c)	(c)
AA-186	44D-677-7	640	0.76	240	410	(c)	-	(c)	(c)	(c)
						Average G_i Value = 31[d]				

[a] Specimen too distorted for measurement.

[b] Measurement not obtained.

[c] Specimen could not be removed from irradiation capsule for measurement.

[d] Specimen No. AA-184, which swelled during irradiation, is not included in the average G_i value.

Table III

EFFECT OF IRRADIATION ON ROUND-ROLLED AND RECRYSTALLIZED SPECIMENS

Spec. No.	Original Rod No.	Rolling Temp., °C	Heat Treatment	Burnup, a/o	Irrad. Temp., °C		Length Change, %	G_i microin./in. ppm burnup	Diameter Change, %	Weight Change, mg.	Hardness Change, R_A
					Surface	Center					
AA-143	34D-695-7	300	18 hrs. at 630° C	0.058	140	230	18.6	290	-6.8	0.2	9.2
AA-144	34D-695-7	300	18 hrs. at 630° C	0.25	200	340	(a)	-	(a)	-836.3	(a)
AA-145	34D-695-7	300	18 hrs. at 630° C	0.37	180	290	(a)	-	(a)	-205.2	(a)
AA-146	34D-695-7	300	18 hrs. at 630° C	0.54	170	280	(c)	-	(c)	(c)	(c)
AA-147	34D-708-7	400	2 hrs. at 625° C	0.039	100	150	8.3	200	-3.2	1.3	8.1
AA-148	34D-708-7	400	2 hrs. at 625° C	0.10	110	170	29.1	260	-9.8	1.8	9.0
AA-149	34D-708-7	400	2 hrs. at 625° C	0.19	120	180	66.3	270	-18.6	2.4	0.1
AA-150	34D-708-7	400	2 hrs. at 625° C	0.58	210	350	(c)	-	(c)	(c)	(c)
							Average G_i Value = 245				
AA-151	34D-706-8	500	2 hrs. at 625° C	0.026	90	130	3.26	120	-1.2	1.7	7.7
AA-153	34D-706-8	500	2 hrs. at 625° C	0.070	90	130	12 0	160	-4.0	1.7	7.4
AA-154	34D-706-8	500	2 hrs. at 625° C	0.12	90	130	23 8	180	-7.8	2.0	8.7
AA-152	34D-706-8	500	2 hrs. at 625° C	0.27	100	160	(a)	-	(a)	1.5	(a)
							Average G_i Value = 155				
AA-155	34D-706-2	600	2 hrs. at 575° C	0.077	180	300	0.73	9.5	0.8	1 3	11.2
AA-156	34D-706-2	600	2 hrs. at 575° C	0.33	240	410	19.6	54	0.8	(b)	(b)
AA-157	34D-706-2	600	2 hrs. at 575° C	0.44	210	350	18.5	39	-1.2	3.1	-1.0
AA-158	34D-706-2	600	2 hrs. at 575° C	0.66	210	350	(c)	-	(c)	(c)	(c)
							Average G_i Value = 34				
AA-159	34D-695-5	640	2 hrs. at 575° C	0.090	210	350	-4.9	-56	4.6	0.7	12.4
AA-161	34D-695-5	640	2 hrs. at 575° C	0.28	230	380	-4.3	-16	8.4	0.5	6.2
AA-162	34D-695-5	640	2 hrs. at 575° C	0.49	240	400	14 5	28	24	4.1	8.9
							Average G_i Value = -36[d]				

[a] Specimen too distorted for measurement. [b] Measurement not obtained.

[c] Specimen could not be removed from irradiation capsule for measurement.

[d] Specimen No. AA-162, which swelled during irradiation, is not included in the average G_i value.

Table IV

EFFECT OF IRRADIATION ON OVAL-ROLLED AND RECRYSTALLIZED SPECIMENS

Spec No.	Original Rod No.	Rolling Temp., °C	Heat Treatment	Burnup, a/o	Irrad. Temp., °C		Length Change, %	G_i microin./in. ppm burnup	Diameter Change, %	Weight Change, mg	Hardness Change, R_A
					Surface	Center					
AA-188	44D-681-4	300	2 hrs at 630° C	0.071	180	280	21.5	270	-8.6	-0.3	9.2
AA-189	44D-681-4	300	2 hrs. at 630° C	0.25	190	320	(a)	-	(a)	-0 3	-
AA-190	44D-681-4	300	2 hrs. at 630° C	0.46	210	350	(b)	-	(b)	(b)	(b)
AA-187	44D-681-4	300	2 hrs. at 630° C	0.55	280	330	(b)	-	(b)	(b)	(b)
AA-191	44D-680-2	400	2 hrs. at 600° C	0.022	75	110	4.1	180	-1.5	0.9	5.8
AA-192	44D-680-2	400	2 hrs. at 600° C	0.058	75	110	13.0	210	-3 9	1.3	4.5
AA-193	44D-680-2	400	2 hrs at 600° C	0 099	80	110	27.8	240	-11 3	1.0	4.0
C-45	44D-680-2	400	2 hrs. at 600° C	0.42	150	250	(a)	-	(a)	2 0	(a)
							Average G_i Value = 210				
C-46	44D-680-6	500	2 hrs. at 600° C	0.041	120	180	7.1	170	-3.6	0.3	8 6
C-47	44D-680-6	500	2 hrs. at 600° C	0.16	150	240	(a)	-	(a)	80 9	(a)
C-48	44D-680-6	500	2 hrs. at 600° C	0.24	130	210	(a)	-	(a)	(c)	(a)
C-49	44D-680-6	500	2 hrs. at 600° C	0.33	130	210	(a)	-	(a)	9 6	(a)
C-50	44D-677-3	600	2 hrs. at 575° C	0 042	120	180	2.3	54	-0.8	-13.9	6.6
C-51	44D-677-3	600	2 hrs. at 575° C	0.12	120	190	8.5	68	-3.2	0 5	7 9
C-52	44D-677-3	600	2 hrs. at 575° C	0.19	120	180	15.8	77	-5.0	4.3	12.9
C-53	44D-677-3	600	2 hrs. at 575° C	0.42	160	250	42 4	84	-14.3	0.1	2.9
							Average G_i Value = 71				
C-54	44D-677-6	640	2 hrs. at 575° C	0.095	220	360	0.06	0.6	1.0	0.7	10.3
C-55	44D-677-6	640	2 hrs. at 575° C	0.32	240	400	6.3	24	1.5	1.5	4.8
C-56	44D-677-6	640	2 hrs. at 575° C	0.53	250	420	(b)	-	(b)	(b)	(b)
C-57	44D-677-6	640	2 hrs. at 575° C	0.74	270	460	(b)	-	(b)	(b)	(b)
							Average G_i Value = 12				

[a] Specimen too distorted for measurement. [b] Specimen could not be removed from irradiation capsule for measurement

[c] Measurement not taken.

Table V

EFFECT OF IRRADIATION ON ROUND-ROLLED AND BETA QUENCHED SPECIMENS

Spec. No.	Original Rod No.	Rolling Temp., °C	Burnup, a/o	Irrad. Temp., °C		Length Change, %	G_l microin./in. / ppm burnup	Diameter Change, %	Weight Change, mg.	Hardness Change, R_A
				Surface	Center					
DE-1-1	2D-230-255	300	0.019	50	55	0.6	32	0.08	-0.8	7.6
DE-11-1	2D-230-255	300	0.027	65	80	0.83	31	0.64	5.1	5.4
DE-4-2	2D-230-255	300	0.044	80	100	1.80	41	0.84	0.2	5.5
DE-7-3	2D-230-255	300	0.062	100	140	1.20	19	3.32	-0.2	3.5
DE-14-2	2D-230-255	300	0.072	110	160	1.21	17	2.20	-0.7	6.5
DE-17-3	2D-230-255	300	0.11	150	220	2.17	19	4.52	-3.0	(a)
DE-19-2	2D-230-255	300	0.14	190	280	2.89	21	2.20	-0.2	(a)
DE-19 1	2D-230-255	300	0.14	190	280	1.59	11	6.71	0.1	(a)
						Average G_l Value =	24			
DE-1-3	34D-708-6	400	0.019	50	55	-0.52	-27	0.24	-0.7	6.8
DE-15-1	34D-708-6	400	0.052	90	120	-3.58	-70	3.48	0.5	5.1
DE-5-1	34D-708-6	400	0.052	90	120	-3.47	-68	3.60	0.9	4.0
DE 8-2	34D-708-6	400	0.063	100	140	-1.69	-27	3.00	-2.0	11.4
						Average G_l Value =	-48			
DE-2-2	34D-706-7	500	0.023	60	75	-0.60	-26	0.44	0.1	6.9
DE-9-1	34D-706-7	500	0.049	85	120	-2.66	-55	1.96	-1.5	4.0
DE-5-3	34D-706-7	500	0.052	90	120	-1.97	-38	1.44	1.7	10.5
DE-15-3	34D-706-7	500	0.052	90	120	2.96	-58	2.72	-0.9	9.7
						Average G_l Value =	-44			
DE-3-1	34D-706-4	600	0.035	70	90	-1.24	-36	1.34	-0.3	4.8
DE-9 5	34D-706-4	600	0.049	85	120	-2.63	-55	3.32	-3.1	5.2
DE-6-2	34D-706-4	600	0.060	95	130	-3.34	-57	4.52	-0.2	-0.2
DE-16-2	34D-706-4	600	0.071	110	160	-3.54	-51	5.88	0.9	(a)
DE-13-1	34D-706-4	600	0.10	140	200	-7.39	-77	8.99	-0.8	7.4
						Average G_l Value =	-55			
DE-3-3	34D-695-3	640	0.035	70	90	-0.18	5	0.44	-0.4	7.1
DE-10-2	34D-695-3	640	0.045	80	110	-1.02	-23	2.20	-6.0	5.1
DE-7-1	34D-695-3	640	0.062	100	140	-1.10	-18	4.48	0.3	8.7
DE-13-3	34D-695-3	640	0.10	140	200	-4.98	-51	9.16	-0.6	9.9
DE-17-1	34D-695-3	640	0.11	150	220	-7.29	-69	8.72	-1.4	(a)
						Average G_l Value =	-33			

(a) Specimen surface too rough for hardness measurement.

Table VI

EFFECT OF IRRADIATION ON OVAL-ROLLED AND BETA QUENCHED SPECIMENS

Spec. No.	Original Rod No.	Rolling Temp., °C	Burnup, a/o	Irrad. Temp., °C		Length Change, %	G_l microin./in. / ppm burnup	Diameter Change, %	Weight Change, mg.	Hardness Change, R_A
				Surface	Center					
DE-1-2	44D-681-5	300	0.019	50	55	-0.44	-23	0.08	-2.0	6.7
DE-11-2	44D-681-5	300	0.027	80	65	-1.19	-44	1.52	12.0	2.0
DE-4-3	44D-681-5	300	0.044	80	110	-2.01	-46	2.36	0.3	5.8
DE-8-1	44D-681-5	300	0.063	100	140	-1.62	-26	4.36	-1.5	7.6
DE 14 3	44D-681-5	300	0.072	110	160	-4.58	-65	5.60	-1.4	4.2
						Average G_l Value =	-41			
DE-2-1	44D-680 3	400	0.023	60	75	-0.88	-38	0.64	-0.8	6.0
DE-11-3	44D-680-3	400	0.027	65	80	-1.74	-64	1.24	6.9	6.1
DE-15-2	44D-680-3	400	0.052	90	120	-1.05	-20	2.80	-1.0	9.7
DE-5-2	44D-680-3	400	0.052	90	120	-2.41	-47	3.96	0	-1.1
DE-8-3	44D-680-3	400	0.063	100	140	3 68	-60	3.88	-32.3	5.1
						Average G_l Value =	-46			
DE-2-3	44D-680-5	500	0.023	60	75	-0.34	-15	0.36	0.5	7.0
DE-9-2	44D-680-5	500	0.049	85	120	-1.36	-28	2.92	-4.9	5.0
DE-6-1	44D-680-5	500	0.060	95	130	-2.09	-35	4.04	-0.1	4.1
DE-16-1	44D-680-5	500	0.071	110	160	-1.93	-27	3.28	1.5	(a)
DE-19-3	44D-680-5	500	0.14	190	280	-3.78	-28	8.27	0.2	(a)
						Average G_l Value =	-27			
DE-3-2	44D-677-4	600	0.035	70	90	-1.31	-38	1.60	-0.1	8.2
DE-10-1	44D-677-4	600	0.045	80	110	-1.03	-23	1.52	-0.9	5.2
DE-6-3	44D-677-4	600	0.060	90	120	-3.52	-60	4.96	0 2	9.6
DE-16-3	44D-677-4	600	0.071	110	160	-3.53	-51	6.56	0.3	(a)
DE-13-2	44D-677-4	600	0.10	140	200	-7.28	-76	9.91	-0.8	(a)
						Average G_l Value =	-50			
DE-4-1	44D-677-7	640	0.044	80	110	-2.19	-50	3.44	0.2	5.1
DE-10-3	44D-677-7	640	0.045	80	110	-1.24	-28	1.88	5.8	4.1
DE-7-2	44D-677-7	640	0.062	100	140	-1.89	-30	3.92	-0.8	-8.6
DE-14 1	44D-677-7	640	0.072	110	160	-4.32	-62	7.36	-0.8	3.6
DE-17-2	44D-677-7	640	0.11	150	220	-7.50	-71	11.7	-1.6	(a)
						Average G_l Value =	-48			

(a) Specimen surface too rough for hardness measurement.

Table VII

EFFECT OF IRRADIATION ON SPECIMENS ROUND-ROLLED AT 600°C WITH SUBSEQUENT REDUCTIONS AT 300°C

Spec. No.	Original Rod. No.	% R. A. at 300° C	Burnup, a/o	Irrad Temp., °C		Length Change, %	G_i microin./in. ppm burnup	Diameter Change, %	Weight Change, mg.	Hardness Change, R_A
				Surface	Center					
BE-25-3	759-A1-7	0	0.0039	50	60	0.23	59	-0.28	0.9	3.8
BE-26-3	759-A1-7	0	0.0044	55	60	0.11	25	-0.44	1.1	4.8
BE-27-3	759-A1-7	0	0.018	90	130	0.43	24	-0.48	1.7	6.6
AA-194	759-A1-7	0	0.57	340	400	(a)	-	(a)	(a)	(a)
						Average G_i Value = 36				
AA-195	759-A1-6	5	0.070	170	270	9.6	130	-3.7	0	7.7
AA-196	759-A1-6	5	0.24	190	320	36.8	130	-9.4	-1.9	4.8
AA-197	759-A1-6	5	0.37	180	300	(a)	-	(a)	(a)	(a)
AA-198	759-A1-6	5	0.58	210	350	(a)	-	(a)	(a)	(a)
						Average G_i Value = 130				
AA-199	759-A1-5	10	0.083	190	320	29.0	310	-10.5	0.2	4.1
AA-200	759-A1-5	10	0.33	250	430	(a)	-	(a)	(a)	(a)
AA-201	759-A1-5	10	0.44	230	380	(a)	-	(a)	(a)	(a)
AA-202	759-A1-5	10	0.68	250	430	(b)	-	(b)	(b)	(b)
						Average G_i Value = 310				
AA-203	759-A1-4	25	0.088	200	330	42.6(c)	-	-13.8	0.2	6.1
AA-204	759-A1-4	25	0.22	200	340	(a)	-	(a)	(a)	(a)
AA-205	759-A1-4	25	0.44	220	370	(a)	-	(a)	(a)	(a)
AA-206	759-A1-4	25	0.60	250	420	(a)	-	(a)	(a)	(a)

(a) Specimen could not be removed from irradiation capsule for measurement.

(b) Specimen too distorted for measurement.

(c) Specimen was partially restrained by capsule because of excessive growth.

Table VIII

EFFECT OF IRRADIATION ON SPECIMENS ROUND-ROLLED AT 600°C AND BETA QUENCHED WITH SUBSEQUENT REDUCTIONS AT 300°C

Spec. NO.	Original Rod No.	% R. A. at 300°C	Burnup, a/o	Irrad. Temp., °C		Length Change, %	G_i microin./in. ppm burnup	Diameter Change, %	Weight Change, mg.	Hardness Change, R_A
				Surface	Center					
BE-33-2	759-A2-7	0	0.0050	55	65	-0.11	-22	-0.04	0.1	6.0
BE-34-2	759-A2-7	0	0.0058	55	70	-0.13	-23	-0.28	-0.3	6.3
BE-35-2	759-A2-7	0	0 022	100	140	-0.15	-7	0.40	0.7	7.6
BE-36-2	759-A2-7	0	0.043	170	260	-0.39	-9	2.5	0	11.4
AA-207	759-A2-7	0	0.077	180	300	-1.9	-25	8.3	1 1	-3.7
AA-208	759-A2-7	0	0.30	220	380	-8.0	-28	23.3	0.9	(a)
AA-209	759-A2-7	0	0.40	200	330	(b)	-	(b)	(b)	(b)
AA-210	759-A2-7	0	0.62	230	390	(b)	-	(b)	(b)	(b)
						Average G_i Value = -19				
BE-29-2	759-A2-6	5	0.0062	60	70	0.25	40	-0.24	1.3	4.2
BE-30-2	759-A2-6	5	0.0067	60	75	0.44	66	-0 20	1 3	5.4
BE-31-2	759-A2-6	5	0.025	110	160	1.8	72	-1.1	1.6	7.0
BE-32-2	759-A2-6	5	0.042	170	250	4.2	98	-1.0	1 8	7.5
AA-211	759-A2-6	5	0 091	210	350	4.4	47	1.4	1.2	9.9
AA-212	759-A2-6	5	0.28	210	360	18.2	60	2.1	22 0	(a)
AA-213	759-A2-6	5	0.47	240	400	(b)	-	(b)	(b)	(b)
AA-214	759-A2-6	5	0.64	270	460	(b)	-	(b)	(b)	(b)
						Average G_i Value = 64				
BE-17-3	759-A2-5	10	0.0040	50	60	0.29	73	-0.64	1.3	4.6
BE-18-3	759-A2-5	10	0.0042	50	60	0.48	110	-0.52	1 3	3.8
BE-19-3	759-A2-5	10	0.017	90	120	2.0	120	-1.1	1.3	6.3
BE-20-3	759-A2-5	10	0.037	160	230	6.0	160	-1.9	1.6	4.7
AA-215	759-A2-5	10	0.080	190	310	16.4	190	2.1	1.0	2.0
AA-216	759-A2-5	10	0.32	240	410	(b)	-	(b)	(b)	(b)
AA-217	759-A2-5	10	0.43	210	360	(b)	-	(b)	(b)	(b)
AA-218	759-A2-5	10	0.66	250	410	(b)	-	(b)	(b)	(b)
						Average G_i Value = 130				
BE-9-2	759-A2-4	25	0.0028	50	55	0.68	240	-0.76	5 8	3.8
BE-10-2	759-A2-4	25	0.0031	50	55	1.1	350	-0.64	2.1	3.7
AA-219	759-A2-4	25	0 093	210	350	42.4	380	-14.5	0.1	0.3
AA-220	759-A2-4	25	0.30	220	380	(b)	-	(b)	(b)	(b)
AA-221	759-A2-4	25	0.48	250	420	(b)	-	(b)	(b)	(b)
AA-222	759-A2-4	25	0.66	250	410	(b)	-	(b)	(b)	(b)
						Average G_i Value = 320				

(a) Specimen too distorted for measurement. (b) Specimen could not be removed from irradiation capsule for measurement.

Table IX

EFFECT OF IRRADIATION ON SPECIMENS ROUND-ROLLED AT 300°C WITH AND WITHOUT INTERMEDIATE ANNEALING DURING ROLLING

Spec. No.	Original Rod No.	Heat Treatment	Burnup, a/o	Irrad. Temp., °C Surface	Irrad. Temp., °C Center	Length Change, %	G_i, microin./in. ppm burnup	Diameter Change, %	Weight Change, mg.	Hardness Change, R_A
BE-1-2	2D-271-A-1	None	0.0021	45	50	1.8	850	-0 92	1.4	1.0
BE-2-2	2D-271-A-2	None	0.0022	45	50	1.7	770	-0.88	1.1	2.5
BE-3-2	2D-271-A-3	None	0.011	70	90	7.5	660	-3.7	1.5	4.1
BE-4-2	2D-271-A-4	None	0.014	85	120	11.5	780	-4.8	2.4	2.0
					Average G_i Value = 770					
BE-5-3	2D-271-B-1	Annealed between rolling passes[a]	0.0026	45	55	0.25	96	-0.48	1.5	5.1
BE-6-3	2D-271-B-2	Annealed between rolling passes[a]	0.0029	50	55	0.28	97	-0.040	1.5	6.9
BE-7-3	2D-271-B-3	Annealed between rolling passes[a]	0.017	85	120	1.7	99	-0.88	1.4	5.6
BE-8-3	2D-271-B-4	Annealed between rolling passes[a]	0.024	110	160	3.2	130	-2.0	1.5	6.1
					Average G_i Value = 105					

[a] Annealing temperatures were varied from 525 to 600°C.

As Rolled Rods (Groups 1 and 2)

Table I shows the results for round-rolled material. The results obtained on oval-rolled material are shown in Table II. The average values of G_i, the growth coefficient, are shown as a function of rolling temperature in Figure 4. Typical specimens from round-rolled rods and from oval-rolled rods are shown in Figures 5 and 6, respectively.

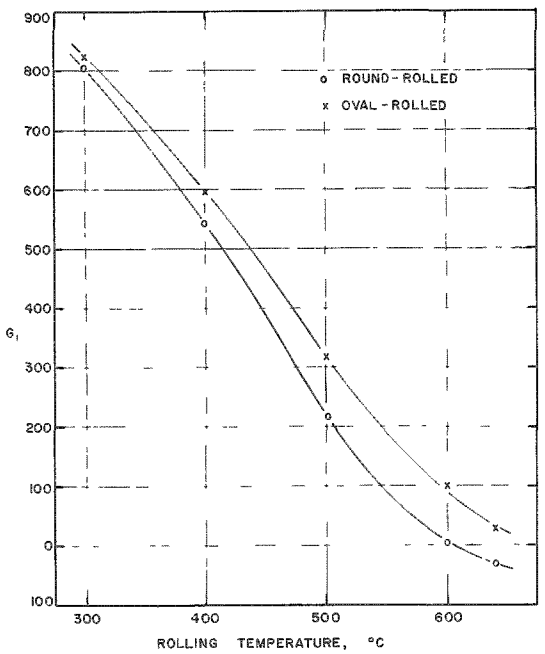


Figure 4. Effect of Rolling Temperature on Irradiation Growth Rates of As Rolled Materials.

The growth rate of the as rolled material decreased rapidly as the rolling temperature was increased. In fact, in the rod round-rolled at 640°C the growth rate became negative, i.e., shrinkage occurred. The growth rates of these specimens and the changes in appearance which occurred can be correlated directly with earlier preferred orientation studies,[3] in which it was observed that the amount of (010) component decreased steadily with increasing rolling temperature.

The specimens which were rolled at 300°, 400°, and 500°C had a texture consisting of (010) and (120) components. Under irradiation, specimens rolled at these temperatures developed a characteristic striated or woody appearance as shown in Figures 5 and 6. Rods rolled at 600° and 640°C showed a (110) component along with some (010). Specimens from these rods, also shown in Figures 5 and 6, developed a generally random surface roughening under irradiation. The shortening under irradiation of the material round-rolled at 640°C is quite likely due to the apparent (100) component observed in rods rolled at that temperature.

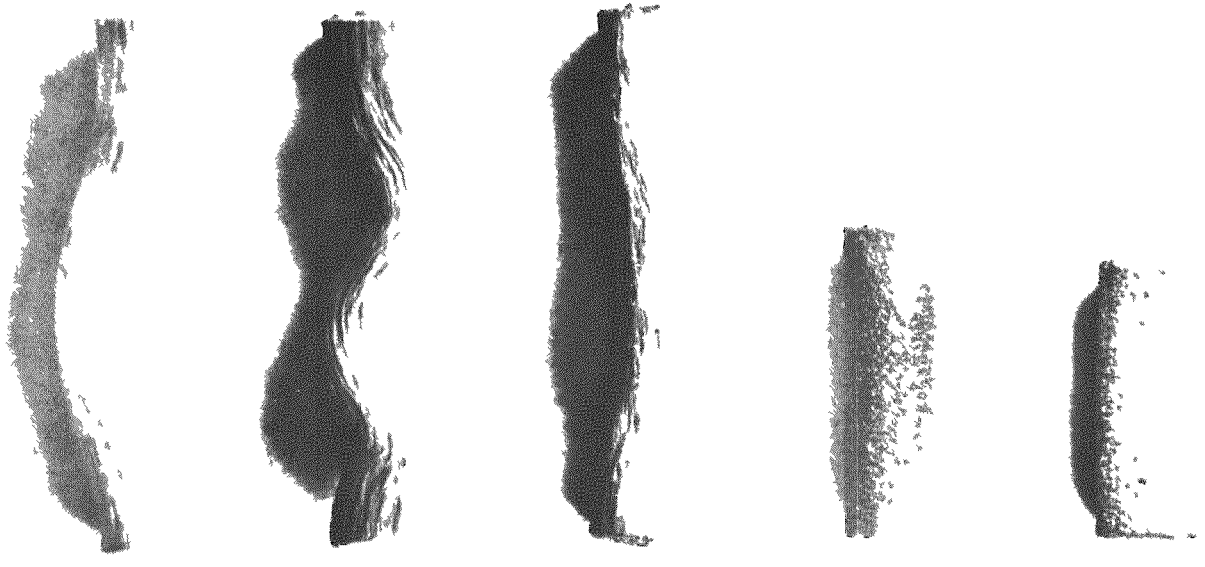
Negative No.	16106	16655	16656	16281	16275
					
Rolling Temp., °C	300	400	500	600	610
Burnup, a/o	0.083	0.13	0.17	0.27	0.40
Avg. G_1, microin./in.-ppm burnup	805	540	215	2.9	-31

Figure 5. Effect of Irradiation on Typical Specimens from Round-Rolled Rods. Magnification 2X.

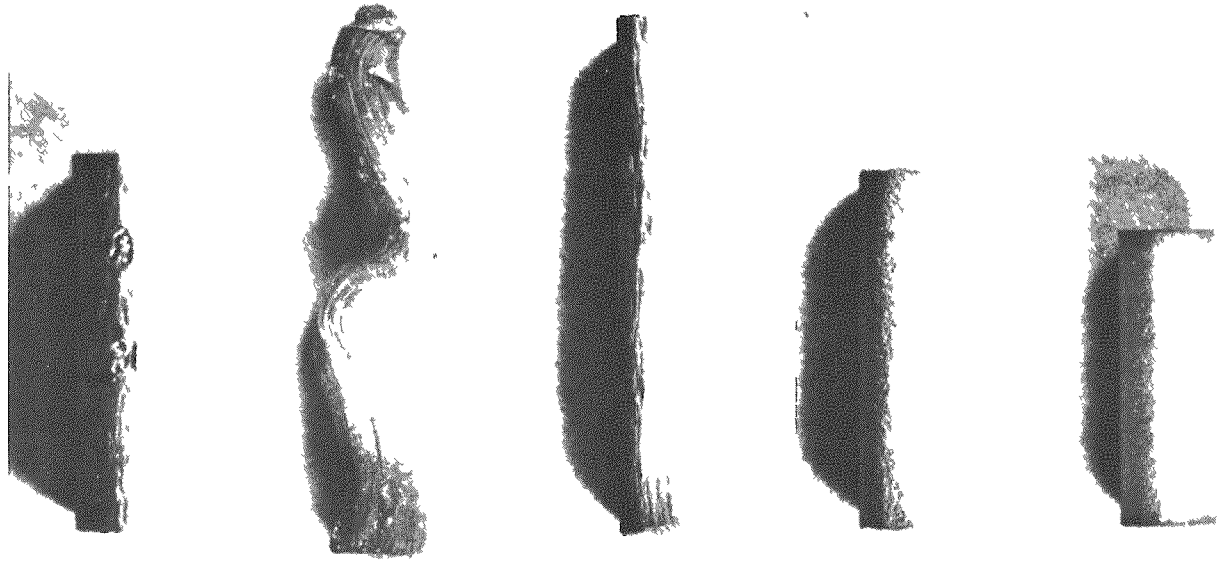
Negative No.	18524	16854	16663	16490	16855
					
Rolling Temp., °C	300	400	500	600	640
Burnup, a/o	0.035	0.16	0.14	0.15	0.085
Avg. G_i, microm./m.-ppm burnup	825	595	320	100	31

Figure 6. Effect of Irradiation on Typical Specimens from Oval-Rolled Rods. Magnification 2X.

The consistently higher growth rate of the oval-rolled material may be related to a radial asymmetry noted in the oval-rolled rod textures,[3] or to a more highly developed (010) component in the rolling direction.

Rolled and Recrystallized Rods (Groups 3 and 4)

Tables III and IV show the results obtained respectively on round-rolled and recrystallized and on oval-rolled and recrystallized material. The average values of the growth coefficient G_i are plotted in Figure 7 as a function of rolling temperature, and typical specimens are shown after irradiation in Figures 8 and 9.

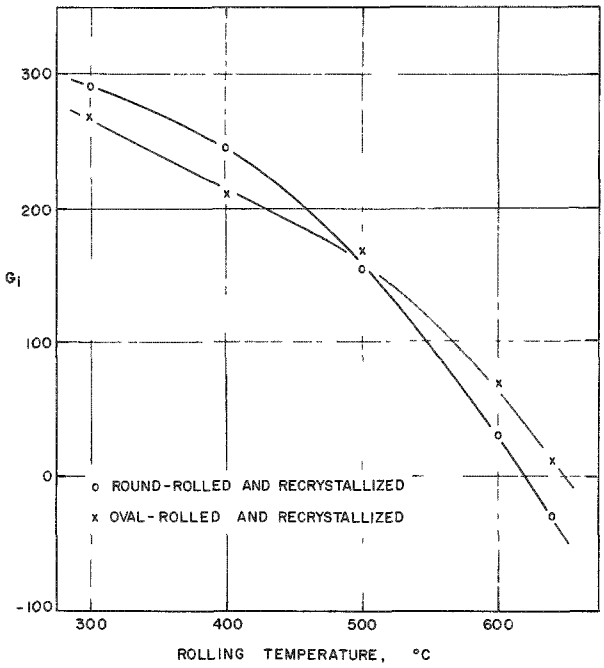


Figure 7. Effect of Rolling Temperature on Irradiation Growth Rates of Rolled and Recrystallized Materials.

The values of G_i appear to be directly related to the preferred orientations that were measured in these rods.[3] It was shown in these studies that when the rods rolled at 300°, 400° and 500°C were recrystallized by annealing, much of the (010) component present in the as rolled texture was replaced with other components, principally the (140). Under irradiation, the recrystallized materials rolled at the above temperatures showed much lower growth rates that were proportional to the decrease in the (010) component.

Similarly, the texture studies showed that the preferred orientation present in the rods rolled at 600° and 640°C was unaffected by the recrystallizing heat treatment used for those materials (2 hours at 575°C). The irradiation results also showed little if any significant differences in growth rate between 600° and 640°C as rolled specimens and those which had been given the recrystallizing heat treatment. On the basis of both the irradiation and texture studies, it appears that the rods which were rolled at 600° and 640°C recrystallized while they were at the fabrication temperature.

Rolled and Beta Quenched Rods (Groups 5 and 6)

The results obtained on round-rolled and beta quenched specimens are shown in Table V.

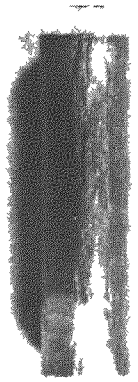
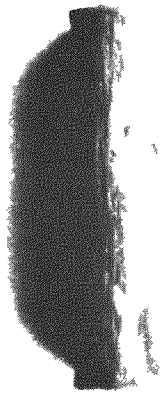
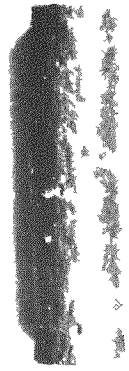
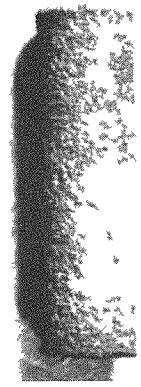
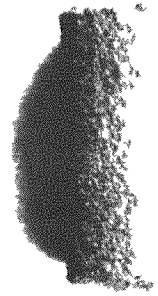
Negative No.	16845	16486	16278	16331	16660
					
Rolling Temp., °C	300	400	500	600	640
Burnup, a/o	0.058	0.10	0.12	0.33	0.28
Avg. G_1, microin./in. - ppm burnup	290	245	155	34	-36

Figure 8 Effect of Irradiation on Typical Specimens from Round-Rolled and Recrystallized Rods. Magnification 2X

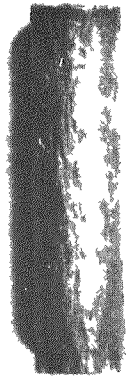
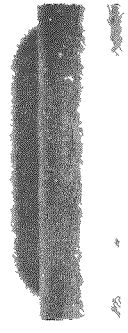
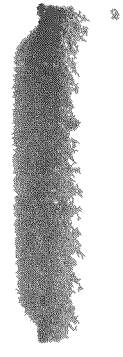
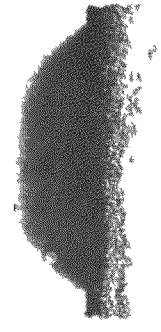
Negative No.	16857	16285	16872	16292	16674
					
Rolling Temp., °C	300	400	500	600	640
Burnup, a/o	0.071	0.099	0.041	0.19	0.32
Avg. G_1, microm./in. - ppm burnup	270	210	170	71	12

Figure 9. Effect of Irradiation on Typical Specimens from Oval-Rolled and Recrystallized Rods. Magnification 2X.

Table VI shows results obtained on the oval-rolled and beta quenched specimens. The irradiation growth coefficients obtained on both types of materials are shown in Figure 10 as a function of rolling temperature.

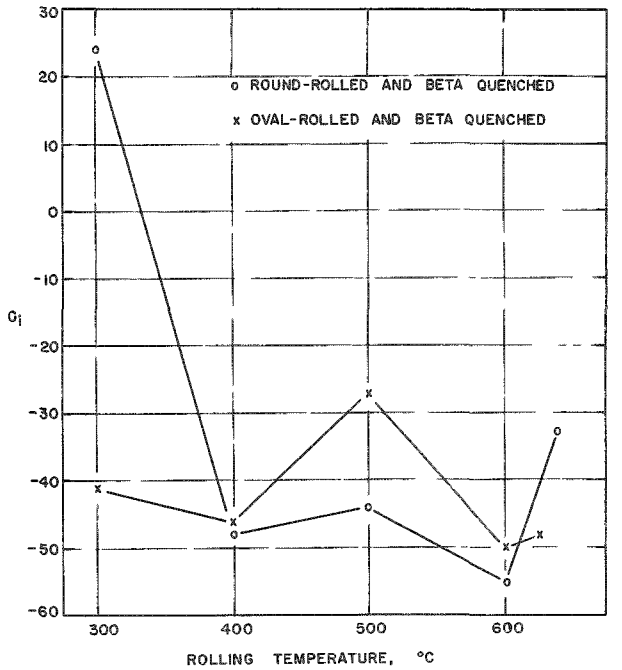


Figure 10. Effect of Rolling Temperature on Irradiation Growth Rates of Rolled and Beta Quenched Materials.

The 300°C rolled and beta quenched specimens elongated under irradiation with an average growth coefficient of 24 microin./in.-ppm burnup. This value checks well with a G_i value of 25 obtained on similar material in another investigation.(10) The specimens round-rolled at all temperatures other than 300°C, and all of the oval-rolled specimens, shortened under irradiation with values of G_i near -45 microin./in.-ppm burnup. Photographs of typical specimens are shown in Figures 11 and 12.

The source of the strong negative growth coefficient in the beta quenched materials (other than that round-rolled at 300°C) is unknown. Unfortunately, texture studies had not been made on the rods used in Groups 5 and 6, so that it is not known whether or not the beta quenching operation caused the appearance of a (100) texture. The shortening under irradiation of the 600°C round-rolled and beta quenched material was confirmed by irradiations made in the Group 8 specimens, as will be described in the next section.

The marked difference in behavior between the 300°C round-rolled material and the 300°C oval-rolled material was unexpected and cannot presently be explained. Without texture determinations one can only speculate why beta quenching had a much more drastic effect on the preferred orientation in the oval-rolled rod as compared to round-rolled material. As can be noted in Figure 10, both types of material rolled at 400°, 500°, and 600°C showed the same general trends in growth rates. The strong influence of heat treatment on the rate of irradiation growth is shown in Figure 13. Shown in the figure are curves of the average growth rate of round-rolled and oval-rolled material with the various heat treatments that were investigated.

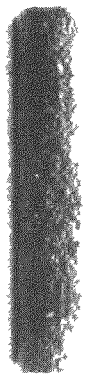
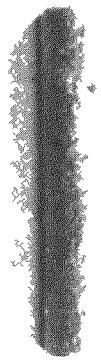
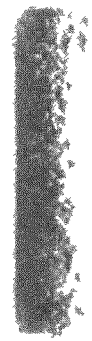
Negative No.	22287	22272	22291	22283	22285
					
Rolling Temp., °C	300	400	500	600	640
Burnup, a/o	0.072	0.063	0.052	0.10	0.10
Avg. G_1, microm./in. - ppm burnup	24	-48	-44	-55	-33

Figure 11. Effect of Irradiation on Typical Specimens from Round-Rolled and Beta Quenched Rods. Magnification 2X.

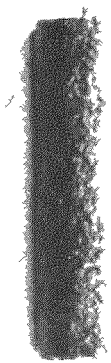
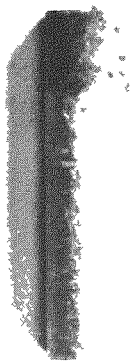
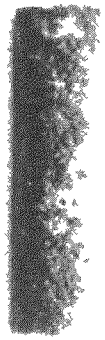
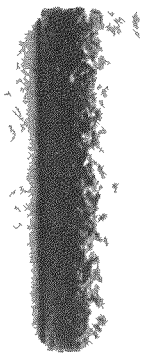
Negative No.	22288	22273	22265	22284	22286
					
Rolling Temp., ^{o}C	300	400	500	600	640
Burnup, a/o	0.072	0.063	0.060	0.10	0.072
Avg. G_1, microm./in.-ppm burnup	-41	-46	-27	-50	-48

Figure 12. Effect of Irradiation on Typical Specimens from Oval-Rolled and Beta Quenched Rods. Magnification 2X.

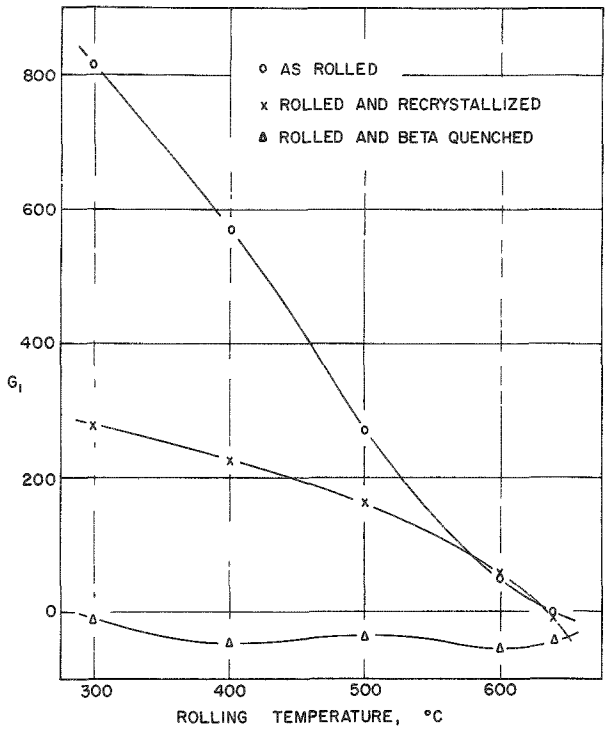


Figure 13

Average Irradiation Growth Coefficients of As Rolled, Rolled and Recrystallized, and Rolled and Beta Quenched Materials.

Rods Rolled to Varying Reductions at 300°C (Groups 7 and 8)

Table VII shows the results obtained on specimens in which the materials had been round-rolled at 600°C prior to further reductions at 300°C. Table VIII shows the results obtained on specimens in which the materials had been 600°C round-rolled and beta quenched prior to further reductions at 300°C. The irradiation growth coefficients obtained on both types of material are shown in Figure 14 as influenced by the amount of reduction at 300°C. Typical specimens are shown after irradiation in Figures 15 and 16.

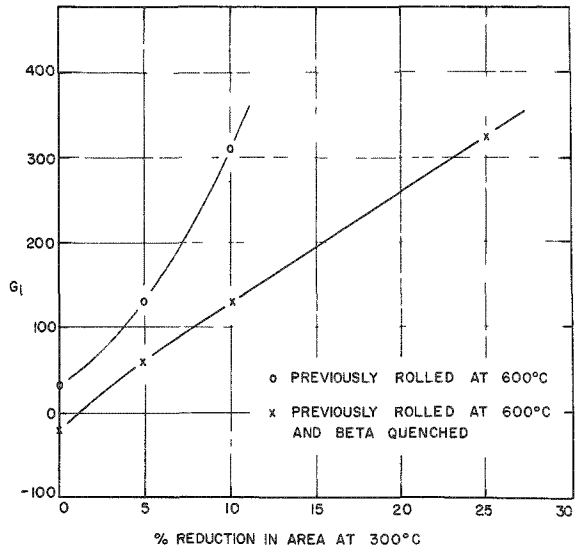


Figure 14

Effect of Rolling at 300°C on Irradiation Growth Rates of 600°C Rolled Materials.

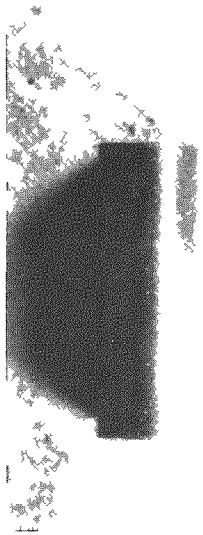
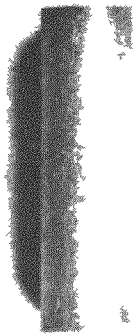
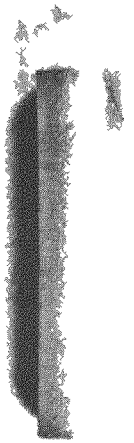
Negative No.	19399	16861	16862
			
Red. in Area, %	0	5	10
Burnup, a/o	0 018	0. 070	0. 083
Avg G_1, microin./in. -ppm burnup	36	130	310

Figure 15. Effect of Irradiation on Typical Specimens Round-Rolled at 600°C and Given Subsequent Reductions at 300°C. Magnification 2X.

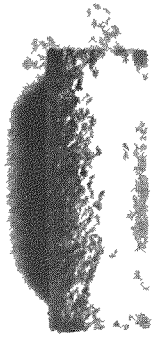
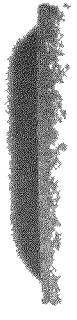
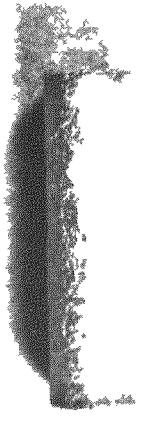
Negative No.	16865	16866	16869	16868
				
Red. in Area, %	0	5	10	25
Burnup, a/o	0.077	0.091	0.080	0.093
Avg. G_1, microm./m. -ppm burnup	-19	64	130	320

Figure 16. Effect of Irradiation on Typical Specimens Round-Rolled at 600°C, Beta Quenched, and Given Subsequent Reductions at 300°C. Magnification 2X.

The previous investigation[2] of the preferred orientations in the rods in this group showed that the amount of (010) component increased steadily with increasing reductions at 300°C. The present results on irradiation growth rates correlate directly with the texture studies. As can be noted in Figure 14, the irradiation growth coefficient increased steadily with increasing per cent reductions. The preferred orientation results did not show significant differences between as rolled starting material or beta quenched material. The present results indicate that somewhat higher growth rates were obtained in the specimens made from rods in which the starting material was rolled at 600°C (Group 7) compared to beta quenched starting material (Group 8). Furthermore, the irradiation growth rate of the rolled material was more affected by the amount of reduction at 300°C than was the beta quenched material.

Rods Round-Rolled at 300°C with and without Intermediate Annealing During Rolling (Group 9)

The results obtained on specimens from these materials are shown in Table IX. As might be expected, the material rolled without intermediate alpha annealing for recrystallization showed higher growth rates than those rods which had been recrystallized during annealing. The results obtained on the unannealed specimens are therefore quite similar to those obtained on the 300°C rolled specimens in Group 1.

The irradiation growth coefficients obtained on the specimens given intermediate annealing were lower than would be expected based on results obtained on the Group 7 and 8 specimens which were given reductions at 300°C. The final reduction in area on the specimens in Group 9 was 47.5 per cent and the average growth coefficient obtained was 105 microin./in.-ppm burnup. Growth coefficients of this order were obtained in the Group 7 and 8 specimens with from only 4 to 7 per cent reduction in area at 300°C. The intermittent recrystallization anneals performed on the Group 9 specimens evidently produced a different texture than was present in the rods used for the Group 7 and 8 specimens.

CONCLUSIONS

1. The rate of elongation of rolled uranium under irradiation increases with decreasing rolling temperature and with increasing reduction of area at 300°C.

2. The rates of elongation are proportional to the amount of (010) component present, or where shortening occurs, to the amount of (100) component.

3. Oval-edge-oval roll passes result in higher irradiation growth rates at a given rolling temperature and amount of reduction than do round roll passes.

4. Recrystallization after rolling effectively reduces the irradiation growth rates of uranium rolled at temperatures of 500°C and lower.

5. Length shortening under irradiation occurred in uranium which was beta quenched after being round-rolled at temperatures of 400°C and above, and which was beta quenched after being oval-rolled at temperatures of 300°C and above.

ACKNOWLEDGMENTS

The experimental measurements before and after irradiation were made by F. Pausche, R. J. Fousek and C. H. Gebo. The author is indebted to R. M. Mayfield, M. H. Mueller and E. S. Fisher for most of the experimental materials used in this investigation, to S. H. Paine, who initiated the study, to R. P. Larsen for burnup analyses, and to D. H. Johnson, R. B. Johns, S. L. Friederichs, and R. S. Kern of the Phillips Petroleum Company for supervising the irradiations at the MTR.

REFERENCES

1. Foote, F. G., "Physical Metallurgy of Uranium," Proc. Int. Conf. on the Peaceful Uses of Atomic Energy, P/555, Vol. 9, 33-68, United Nations, Geneva (1955). Also, Progress in Nuclear Energy, Vol. 1, Series V, 81-201, Pergamon Press, London (1956).

2. Mueller, M. H., Knott, H. W. and Beck, P. A., "Effect of Varying Reduction on the Preferred Orientation in Rolled Uranium Rods," ANL-5194 (1954).

3. Mueller, M. H. and Knott, H. W., "Effect of Rolling Temperature on the Preferred Orientation in Rolled Uranium Rods," ANL-5329 (1957).

4. Thomas, W. R., "The Effect of Cold Work on the Irradiation Stability of Uranium," AECL No. 591 (1958).

5. McDonell, W. R., "Preferred Orientation of Cold-Rolled and Recrystallized Uranium Plate," DP-258 (1957).

6. McHargue, C. J. and Jetter, L. K., "Preferred Orientation in Uranium, Thorium, Zirconium and Beryllium," Progress in Nuclear Energy, Vol. 2, Series V, 430-459 (1959).

7. Sergeyev, G. Y., Titova, V. V., Nikolayeva, Z. P., Kapteltsev, A. M. and Kolobneva, L. I., "The Influence of Fabrication Methods on the Structure and Properties of Uranium," Proc. Second U.N. Int. Conf. on the Peaceful Uses of Atomic Energy, P/2307, Vol. 6, 25-33, United Nations, Geneva (1958).

8. Kelman, L. R., "Dimensional Changes in Uranium Under Thermal Cycling," TID-68, 7-40 (1949).

9. Paine, S. H., Persiani, P. J. and Murphy, W. F., "Irradiation of Prototype CP-4 (EBR-I) Reactor Fuel Slugs in the CP-3 Goat Hole," ANL-5855 (1958).

10. Kittel, J. H. and Paine, S. H., "Effects of High Burnup on Natural Uranium," ANL-5539 (1957).

11. Zaimowski, A. S., Sergeev, G. Y., Sitova, V. V., Levitsky, B. M. and Sokunsky, Y. N., "Influence of Uranium Structure and Properties Upon Its Behavior Under Irradiation," Proc. Second U.N. Int. Conf. on the Peaceful Uses of Atomic Energy, P/2191, Vol. 5, 566-573, Geneva (1958). Also in Atomnyi Energiya 5, 412-420 (1958).

12. Chiswik, H. H., "Effects of Preferred Orientation and Grain Size on Dimensional Stability of Uranium on Thermal Cycling and Irradiation," ANL-4955 (1956).

13. Shype, O. K., Cummings, W. V. and Watts, E. C., "Effects of Various Preferred Orientations on the Dimensional Stability of Uranium," HW-54605 (1958).

14. McDonell, W. R., "Quantitative Correlation of Irradiation Growth With Preferred Orientation in Uranium," DP-420 (1960).

15. Paine, S. H. and Kittel, J. H., "Preliminary Analysis of Fission Induced Dimensional Changes in Single Crystals of Uranium," ANL-5676 (1958).

16. Turkalo, A. M., "The Dimensional Stability of Uranium Single Crystals and Polycrystals During Irradiation and Thermal Cycling," KAPL-1044 (1954).

17. Mayfield, R. M., Chiswik, H. H. and Macherey, R. E., "Mechanical Properties of Rolled Uranium Rods," ANL-5296 (1956).

18. Paine, S. H. and Kittel, J. H., "Irradiation Effects in Uranium and Its Alloys," Proc. Int. Conf. on the Peaceful Uses of Atomic Energy, P/745, Vol. 7, 445-454, Geneva (1955).

19. Macherey, R. E. and Zegler, S. T., "The Manufacture of Internal Blanket and Fuel Blanket Slugs for the Experimental Breeder Reactor," ANL-5132 (1953).

20. Fisher, E. S., "Preparation of Alpha Uranium Single Crystals. Part II - Strain Anneal Method," ANL-5160 (1954).