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METALLURGY DIVISION

URANIUM SAMPLES FOR PILE RADIATION EXPOSURE

A. G. H. Andersen

CLASSIFICATION CHANGED TO: DECLASSIFIED
BY AUTHORITY OF: TID-1148
BY: R. Morrison 7/10/57

DATE ISSUED: MAR 31 1950

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URANIUM SAMPLES FOR PILE RADIATION EXPOSURE

(Preparation and Physical Properties of 3 mm Square Wires of Natural and Enriched Uranium)

Resume

Three ORNL reactor slugs (1-1/16 in. diam) and two uranium ingots (1 in. square) enriched with U^{235} to 6.5 and 2.7 percent, respectively, were worked into wires .119 in. square. The ingots were α-rolled into 3/8 in. round rods, α-swaged to .162 in. round, squared in a rolling mill and finished to size by drawing through square dies.

The metal was worked in Bldg. 101-D, and vacuum annealed in the Physics Department's laboratory in the Pile Building. Metallurgical Engineer in charge: Dr. A. G. H. Andersen. Technician carrying out operations: Mr. R. T. Clem and various helpers. The metallographic work was furnished by Mr. R. J. Gray.

Introduction

The wires are intended to be cut up into 3 in. long test specimens, exposed to neutron radiation in the Hanford Pile and examined for mechanical and physical properties by the Physics of Solids Section of ORNL. This work was originally requested by Dr. S. Siegel, former chief of the Physics of Solids Section, in March 1948; however, it was not until March, 1949, that the enriched material was received by the Metallurgy Division, no member of which had had previous experience with uranium fabrication. Meanwhile, sufficient skill in such fabrication was acquired by practice on X-10 slugs.

When enriched uranium is worked above 300-400°C, it is necessary to protect the metal against oxidation. Below 300°C, the metal may be worked without protective casing, with only slight oxidation. The present metal was worked at temperatures dropping from 300° to 200°C with frequent reannealing at 625°C. During heating at 300°C the metal was submerged in oil. While exposed to the air during working, oxidation was superficial, and the amount of

[redacted]

oxide produced was 1 to 1½ percent of the weight of metal. Various other methods of working were tried and rejected. Thus ¼ in. square bars were plated with nickel or with silver and rolled at 600°C, but the plates did not serve their purpose of preventing oxidation. Nickel plates formed brittle alloys with uranium, and silver plates frequently rolled into loosely fitting cases. The plates broke and oxidation resulted. It appears probable, however, that an adherent silver coat of 2 mills can be applied to ¼ in. bars and remain intact until the bars are reduced to .12 in. square wire.

It was tried to forge ORNL Reactor slugs at 800°C. The pieces were encased in copper and in mild steel. During forging under an air hammer, the casings broke and exposed the uranium to oxidation. The casings had formed brittle alloys with the uranium.

Larger sections, 1 in. to 3/8 in. in diameter, were easily rolled at 500°C to 600°C, but the oxidation losses amounted to 20 percent, and, although the bulk of the oxides can be recovered, such oxidation cannot be tolerated when working enriched material. Both the α-radiation activity and the expense of the enriched material demand that no weighable amounts be left around in the shop equipment, nor allowed to escape into the atmosphere of the laboratory. One hundred percent accountability is required. In order to make it possible to account for all the material, metal samples as well as waste products, close checking of the weights of the metal, before and after each step in the operation, becomes necessary. A simple system of accounting by repeated subtractions, like that used in bank check-account statements, serves well for keeping track of the material.

Protection of the metal against oxidation by use of helium during rolling proved impractical.

The Ingots

One ingot of natural uranium and two ingots of enriched uranium were received through the Accountability Office. The process of melting and casting the ingots is not known to the Metallurgy Division. The ingots had been machined to 1 sq in. × 3-3/8 in. long before they were received at ORNL. Spectrographic analyses of the ingots showed the usual amounts of metal impurities. Al, Ca, Cr, and Cu were present in amounts from 10 to 100 ppm while

the figures for Fe, Mn and Mg were less than 1000 ppm. Boron showed very faint lines. ORNL reactor slugs were processed into bars similar to the special metal. Spectrographic analysis of both types of metal were reported to check well except for the boron lines which did not show in the ORNL reactor slugs. The spectrographic analyses were done by Cyrus Feldman.

Chemical analysis for carbon was carried out by P. C. Westerdahl. Samples from ORNL slugs Nos. 6 and 7 showed .19% C and .15% C, respectively. Enriched metal samples gave results as follows: No. 9 (6.5% U^{235}) - .1 - .33% C; No. 10 (2.5% U^{235}) .13 - .5% C. The higher carbon content of some of the enriched specimens is reflected in the micro-structures.

The Working Procedure

The series of steps required to reduce the uranium ingots from 1 sq in. to .119 sq in. depended upon the available working equipment in the Metallurgy Division. These steps are enumerated in Table I.

Annealing

The specimens were annealed in a 3 in. diam quartz tube furnace at less than 1 micron vacuum. Rods larger than 5/16 in. were annealed at 900°C for two hours, while those of smaller diameter were annealed at 625°C for three hours.

It was necessary to degrease the specimens carefully in order to avoid errors in weight losses after annealing and working processes. Caustic degreasers worked well, with very small metal losses.

Pickling

Preparatory to rolling and swaging, the rods were heated in oils to 300°C. Silicone oil (DC 550 fluid, Dow-Corning Corporation) was tried on normal uranium and found to be excellent for the purpose. Since, however, quenching oil (Texaco) also proved to be a satisfactory heating medium slightly below 300°C, the latter oil was used for heating the enriched uranium. Observation showed that heating in both oils caused an oxide film to form on the surface

TABLE 1

Cycle A

1. Weighing of 1 in. ingot
2. Annealing in vacuum at 900°C for 2 hours
3. Weighing
4. Heating for at least 20 minutes in oil at 300°C
5. Rolling from 1 in. square to ¾ in. round at 300°C to 200°C in 5 roll passes, using 10 to 20 sizes of openings, adjusting the center distance between rolls to give 3% to 5% reduction per pass with each opening. The roll surfaces are kept at 200°C
6. Degreasing in alkaline solution, rinsing in water and in alcohol
7. Weighing of ¾ in. rod
8. When deoxidation of surface is required, pickle in strong nitric acid for 5 to 10 seconds; rinse in water and alcohol

Cycle B

1. Weigh clean, ¾ in. rod
2. Reanneal in vacuum at 900°C for 2 hours
3. Weigh the annealed ¾ in. rod
4. Heat for 20 minutes or more in oil at 300°C
5. Roll from ¾ in. round to ½ in. round at 300°C to 200°C in 6 roll openings using 10 to 20 passes, at 3% to 5% reduction per pass, as in A-5

6, 7, 8 — Similar to Cycle A-6, 7, 8

Cycle C

1. Weighing
2. Annealing
3. Weighing
4. Heating

As in A-1, 2, 3, 4

5. Rolling from ½ in. round to 3/8 in. round. All other conditions kept as in A-5

TABLE 1 (Cont'd)

6, 7, 8 As in A-6, 7, 8

9 Weighing of rod before cutting

10 Cutting by hack saw, weighing and saving the chips

11 Weighing of metallographic samples

12 Weighing of croppings

Cycle D

1 Weighing of remaining rod

2 Annealing as in A-2

3 Weighing as in A-3

4 Heating as in A-4

5 Swaging from 3/8 in. round to 9/32 in. (32% reduction in area) in hot swaging dies at 200°C

6, 7, 8 As in A-6, 7, 8

9 Weighing

10 Cutting of metallographic samples and croppings. Weighing and saving chips

11 Weighing of metallographic samples

12 Weighing of croppings

Cycle E

1 Weighing of remaining rod

2 Annealing 9/32 in. rod for 3 hours at 625°C

3 Weighing 9/32 in. rod

4 Cutting of metallographic samples and croppings. Weighing and saving chips

5 Weighing of metallographic samples

6 Weighing of croppings

7 Weighing of remaining rod

8 Heating in oil for 20 min. at 300°C

9 Swaging from 9/32 in. round to .193 in. round. Dies at 200°C. Rod heated by flame in passing

10 Cutting of metallographic samples and croppings. Weighing and saving chips

TABLE 1 (Cont'd)

11 Weighing of metallographic samples

12 Weighing of croppings

Cycle F

1 Weighing of remaining .193 in. rod

2 Annealing in vacuum at 625°C for 3 hours

3 Weighing of annealed rod

4, 5, 6, 7, 8 Same as E-4, 5, 6, 7, and 8

9 Swaging from .193 in. to .162 in. round

10 Heating for at least 20 min. at 300°C in oil

11 Squaring .162 in. round in diamond passes on hand-crank rolling mill and rolling to .130 in. square. Rolls at 200°C; rod heated by flame in passing

12 Weighing

13 Annealing in vacuum at 625°C for 3 hours

14 Weighing

15 Cutting, weighing and saving of chips

16 Weighing of metallographic samples

17 Weighing of croppings

Cycle G

1 Weighing of remaining rod

2 Pointing and drawing rod in square dies using Stancoat No. 1 for lubricant, temperatures 200°C to 100°C

Two passes through .127 in. square die

Two passes through .119 in. square die

of the uranium. The metal oxidized further while it was exposed to the air during rolling and swaging, at temperatures dropping from 300°C to 200°C.

At first, it was thought necessary to remove the oxide film before annealing. This was easily done by pickling for 5 to 10 seconds in strong nitric acid, followed by a distilled water rinse, an alcohol rinse, and drying. The weight losses averaged .07% of the bars in each pickling operation. It was soon found that a good vacuum could be maintained during annealing, even though the bars were charged without prior pickling. The metal was slowly heated in the furnace with the vacuum pump going. Much of the oxide film evidently evaporated, for under these conditions the vacuum fell rapidly from 1 micron to about 100 microns and then slowly rose again and attained a fraction of a micron; hence pickling was discontinued.

Rolling

The metals were rolled on a standard machinery company 6 in. × 10 in. rolling mill. Starting with a box pass of 1 in. × 15/16 in., the annealed 1 in. square ingot was reduced to ¾ in. diam in 5 succeeding round roll passes to ½ in. diameter, reannealed and rolled through 6 passes to 3/8 in. diameter.

The rolls were maintained at about 200°C by heating with a gas flame, and the metal was heated while passing back and forth through the mill. The roll spacing was frequently changed by operating a motor-driven screw-down. These adjustments are required in order to keep the reduction per pass down to 3 to 5 percent. When heavier reductions are given, especially if the metal is cold, experiments on normal metal have revealed a tendency to form internal cracks, even though the surface remains intact. This tendency has been found to a still higher degree in swaging. The metal was kept hot by heating in oil at 275°C between passes.

Swaging

A hand-crank operated rolling mill provided with diamond passes was available for squaring the rods. The largest size uranium that this mill can roll properly at 200°C to 300°C is about 3/16 in. square. It was, therefore, decided to swage the rods from 3/8 in. to .163 in. The high-speed steel swaging-dies

were maintained at about 200°C and the rods were heated by a gas flame as they passed into the dies. Before each pass the rods were heated in oil at 275°C for at least 20 minutes. Swaging had to be done carefully, as previous trials had shown that rods which were given a reduction of more than 2½ B & S gage die-sizes easily cracked. Thus, it had frequently been observed that rods which appeared sound of surface would crack up in annealing. The cracks always occurred along the axis of the rods, and the rods twisted and coiled, frequently splitting into several strands. In other rods the cracks would appear only upon microscopic examination. In this manner rods produced from the specially cast ingot of natural uranium (Metal No. 8) cracked up so consistently that no wires could be produced.

This ingot was distinctly more difficult to work than the ORNL reactor slugs worked previously, and the size of drafts used with the latter were therefore reduced when the two remaining specially cast metals (No. 9 and No. 10) were worked. In order to avoid cracking, the total amount of cold work between annealings were reduced, and the rods were reannealed at 625°C for 3 hours, after being swaged in only 4 or 5 dies with a maximum reduction of about 30 percent.

Hand-Crank Rolling Mill

After heating the swaged bars overnight in oil at 275°C, rolling was resumed in a 3 in. × 4 in. hand-crank operated rolling mill. The bars, at 280°C, were passed through rolls provided with diamond passes, squared up and reduced to .133 in. or .125 in., respectively, before final anneal. No particular difficulty was encountered. Care is required, since the corners of sharply squared bars have a tendency to develop fine cracks which are very detrimental in the succeeding drawing operation. The hand rolling mill did not allow rolling to close dimensions, and the rods after rolling also needed straightening. The available equipment for performing these operations is a Baldwin Southwark 120,000 lb tensile testing machine, die holder and square dies.

Wire Drawing in Square Dies

Preliminary tests on normal uranium had shown that drawing through square dies is difficult. The metal should preferable be repeatedly α-worked and

α-annealed before drawing. This promotes formation of a very fine, clear-cut structure of small equiaxial grains, with few of the mosaics of grains within grains, which are frequently seen in photomicrographs of uranium after it has gone through allotropic changes. Further, the rods should be free from cracks, especially transverse cracks at the corners. If the drawing is done too hot, the metal remains weak and deforms locally at comparatively low stresses; the rods neck heavily under the die and fractures. If the metal is drawn too cold, resistance to deformation causes the tensile stresses to rise, with little necking until the rod breaks in or near the die exit.

A temperature of 150°C proved serviceable. Lubrication of the rods is required, for without it the dies tend to pile the metal up in the corners at the die entrance, causing faulty corners which soon result in fracture below the die. Oils and greases, hot or cold, gave poor service as lubricants. Calcium and aluminum steareates worked much better, but the best service was obtained with "Stancoat #1," a ferric sulphate base coating-material. This substance was stirred up in water and painted on the slightly oxidized surface of the rods. These were subsequently baked at 240°C. A rough coating was thus produced. After passing through the first die once, this coat has a dark, glossy, enamel-like appearance. Apparently some combination of the uranium oxide film and the drawing compound occurred. This coat stayed on through subsequent passes.

Two dies were used. The reduction given in the first die is .133 in. to .126 in. or 11 percent. In the finishing die, the reduction is .126 in. to .119 in. or 11.5 percent. This makes a total reduction of 20 percent since the previous 625°C anneal. The loads required for drawing varied with the reductions given in a single pass and with the total reductions given since the preceding anneal. Loads in the .126 in. die would run up to 2100 lbs (130,000 psi) but usually did not exceed 1600 lbs (114,000 psi) to 1800 lbs (126,000 psi). These stresses are close to the yield points of the metal at 100°-200°C, and the danger of breakage during drawing is ever present. The wires were drawn through the dies by moving the upper platen by its motor-drive, about 14 in. per minute. No means for varying the speed and studying its effect was at hand.

The Products

Close records of all the weighings were kept, and these are summarized in Table II. It is, therefore, possible to tabulate the distribution of the

TABLE II

ENRICHMENT	VACUUM FURNACE	WORKING EQUIPMENT	CLEANING SOLUTIONS	METAL-CHIPS AND FILINGS	CROPPING SCRAP	METALLOGRAPHIC SPECIMENS	3 MM SQUARE WIRE	
DISTRIBUTION OF ENRICHED URANIUM PRODUCTS AFTER WORKING, IN GRAMS								
2.7% #10	.485	12.722	2.950	27.116	465.340	69.743	482.004	1060.35
6.5% #9	.362	15.560	2.112	27.566	398.029	62.465	551.925	1058.02
Totals	.847	28.282	5.062	54.682	862.369	132.208	1033.929	2118.37
DISTRIBUTION BY PERCENT, NATURAL AND ENRICHED URANIUM								
0-#7	.19	.55	.31	17.0	24.0	18.5	39.95	
0-#6	.11	.38	.34	6.18	11.0	10.58	70.58	
2.7%-#10	.046	1.20	.28	2.56	43.88	6.56	45.46	
6.5%-#9	.034	1.47	.20	2.60	37.62	5.90	52.17	

BULK OF WASTE

SOLIDS		SOLUTIONS & SLUDGES	
High - Activity	3.55 kg	NaOH	.784 liters
Medium - Activity	1.80 kg	HNO_3	1.083 liters
Low - Activity	17.45 kg	Water	2.520 liters
		Alcohol	.269 liters
		Quenching Oil -	.550 liters

original metal into various fractions indicating the amount of metal in each kind of product obtained. These products are according to Table III (3*b*) 3 mm square wire, (3*a*) metallographic specimens, (2*c*) cropping scraps, (2*b*) metal dust and chips from sawing, filing, chipping and small broken fragments from rolling scrap, (2*a*) cleaning solutions, and (1) the containers, wraps, and packages used, together with oils, tools, and furnaces, and all bench and floor sweepings. Products (3*a* and *b*) and(2*b* and *c*) are solid metals. Products (2*a*) are solutions containing easily recoverable metal. The waste products under (1) were divided into three groups and stored in separate containers, according to the conjectured percentage of metal in each. Table IV shows the distribution of the metal after the work had been finished. Items I, II and III of Table IV are either metals or solutions easily converted to metals with very small losses. The figures were obtained by actual weighing. Item IVa shows 6 kg of high and medium activity waste material. By subtraction of weights, as in Table III, it has been estimated that this bulk contains 29.13 grams of metal. IVb shows 17.5 kg bulk of low activity waste materials estimated to contain 6.75 grams of metal, less actual losses in air ducts, decontamination and daily cleaning of the laboratory.

It is to be noted that in order to keep complete accounts all metal-fractions, including filings and chips, should be weighed separately after each operation, along side the wire rods each group of metal-fractions of identical enrichment should be stored together and never mixed with fractions having dissimilar enrichment percentages.

Physical Properties

In order to control the working processes, metallographic samples were cut from the bars at frequent intervals, as shown in Table I. The samples were macroscopically and microscopically examined for cracks as well as for structures. Photo-micrographs of representative samples are given in Figs. 1-44.

The photo-micrographs show the structures of the three types of metal, ORNL reactor slugs (Metals Nos. 5, 6, and 7), specially prepared natural uranium, (Metal No. 8) and specially prepared enriched uranium, (Metals Nos. 9 and 10). The structures of the metals after various stages in working are

TABLE III

Disposition of Metal by Subtraction of Weighings

	INGOT NO. 10 (2.7% Enriched)		INGOT NO. 9 (6.5% Enriched)		NO. 9 AND NO. 10 (Combined)	
(1) Waste Materials						
a From Working Tools	12.722		15.560		28.282	
b Vacuum Furnace	.485		.362		.847	
c Floor Sweepings	?		?		?	
		13.207		15.922		29.129
(2) Scrap						
a Cleaning Solutions		2.950		2.112		5.062
b Metal and Chips Filings	27.116		27.566		54.682	
c Croppings	465.340		398.029		863.369	
		492.456		425.595		918.051
(3) Metal Specimens						
a Metallographic	69.743		62.465		132.208	
b 3 mm sq wire	482.004		551.925		1033.929	
Total Specimens		551.747		614.390	1166.137	1166.137
Items (2) and (3)		1047.153		1042.097	2089.250	
						2089.250

TABLE IV

Balance Sheet

		GRAMS	GRAMS	GRAMS
I.	Products			
	a Metallographic specimens	132.208		
	b Wire Product	1033.929		
			1166.137	
II.	Scrap			
	a Metal Chips and Filings	53.800		
	b Croppings	856.054		
			909.854	
III.	Cleaning Solutions		5.062	
IV.	Chemical Analysis Samples		1.399	
V.	Waste Materials			
	a 6 kg Bulk. High and Medium activity High percent recoverable.	29.129		
	b Low activity material and floor sweepings. 17.5 kg bulk, low recovery percentage; air duct and decontamination losses	6.750		
			35.879	
	Total metal content		2118.331	
	Materials received			2118.331

shown. These stages and all other pertinent data are given in the captions and need little explanation.

It may be seen that all three types of metals contain numerous inclusions which probably consist mainly of carbides. The specially prepared metals generally show larger amounts of these inclusions than the ORNL reactor slugs, and the amounts appear to be larger in Metal No. 9, 6.5% enriched, than in No. 8, the normal special metal, while No. 10, the 2.7% enriched metal shows amounts of inclusions intermediary between Nos. 8 and 9. The amounts of inclusions are not the same in all specimens from one metal grade, so that segregations may have existed in the original ingots. The precise method of preparing the ingots is not known, but it is likely that they were cast in graphite molds.

Figures 33 to 43, inclusive, show the structures of some specimens that were polished by hand and etched chemically in order to retain the carbide inclusions. By electrolytic polishing, the inclusions are easily destroyed, leaving cavities in their place. It may be seen that ingots Nos. 9 and 10 contain enough carbon to cause pearlitic structures after certain heat treatments, while this never was the case with the ORNL reactor slugs. The carbon also may be seen to have a tendency to form intergranular envelopes such as is shown typically in Fig. 37. The higher carbon content of some specimens from ingots Nos. 9 and 10 and the unfavorable micro-structures that carbon frequently causes may account for the greater tendency of cracking in working, which the specially cast uranium possesses.

Mechanical Properties

As further control of the metal during the processes of working and annealing, hardness tests were usually made before and after annealing bars of diameter 3/8 in. and less.

In Table V are listed the Rockwell hardness numbers of normal uranium and the two grades of enriched uranium in various stages of preparation. The rods from which the hardness test specimens were taken have been repeatedly rolled and reannealed at the temperatures indicated in the second column of Table V. The smaller specimens have thus passed through a number of cycles of working below 300°C and reannealing at 625°C. Time of annealing at 625°C was 3 hours

and at 900°C, ½ to 2 hours. Actually the rods were preheated, preparatory to rolling and swaging, at 280-290°C. It is estimated the temperature dropped during working to 200°C. The temperature of the metal during wire-drawing varied and was difficult to control. Best results in drawing were obtained at about 150°C.

It may be seen from Table V that the hardness numbers of the specimens that were annealed at 625°C are from 6 to 12 points higher than those annealed at 900°C. Annealing at 625°C evidently does not completely soften the specimens in 3 hours, but microscopic examination of annealed specimens showed that the elongated grains resulting from cold working have become equiaxial without showing grain growth. This difference in hardness is possibly an effect of grain size. The inclusions which are strung out during working remain so after annealing and frequently give the impression of a fiber structure.

In general, the structures after 3 hours annealing at 625°C are excellent.

Apparently Nos. 9 and 10 are harder than the other samples after annealing, and after working excepting the final drawing. This may be due to differences in chemical composition between both groups of metals, the X-10 slugs and the special metal. There may also be a chemical difference between the natural uranium sample No. 8 and the enriched samples Nos. 9 and 10. Spectrographic analyses do not reveal significant differences between the various samples of uranium, but carbon analysis shows that metals Nos. 9 and 10 contain more carbon than Nos. 6 and 7. This is mentioned in more detail under the description of the ingots.

Tensile test data on normal and on enriched uranium are presented in Table VI. The reduction of area and elongation of some of the normal uranium specimens are low and show much scatter. This is believed to be due to the condition of the specimens, which were not as free from corner cracks as the enriched metal specimens.

The latter were prepared by using the experience gained in preparing the former. The table shows both tensile strength and the fracture stress obtained by dividing the load with the area at fracture. The tensile strengths compare well with natural α-rolled uranium.

Figures 44 through 50 show load strain curves of annealed and cold worked samples .12 in. square. The curves were obtained with Peters Company standard micro-former automatic recording devices, attached to our Baldwin Southwark 120,000 lb tensile testing machine. The diagrams have been reduced in size

during reproduction. In all diagrams, the larger divisions of the abscissa represent 1 inch of chart, and in all cases, this distance corresponds to a strain of 1 in. per inch. There appears to be little difference in the flow strengths between the various grades of metal, whether in hard drawn or annealed state.

Prevention of Contamination

Elaborate precautions were taken to prevent contamination of the laboratories. Smear samples were taken from all machines and tools used, both during and after working by representatives from the Health Physics Department. Similarly, the air was sampled near the working points and throughout the rooms. Heavy contamination of the tools is unavoidable, and decontamination of all working surfaces is required after each working period.

It soon appeared that rolling, swaging and drawing of uranium will also contaminate the air, floors and other surfaces throughout the room in which uranium is worked. From a health standpoint, therefore, such operations must be classed with machining. Hoods have been installed over some working areas and flexible suction ducts have been provided at all tool points for working uranium. It is expected that by these means general contamination of the work rooms will be avoided and the local contamination at tool points will be readily controlled.

Photo-Micrographs

The photo-micrographs Figs. 1 to 32 are at X100, polarized light, and show electrolytically polished and electrolytically etched surfaces. Figures 33 to 43 show photo-micrographs by vertical illumination of specimens chemically etched in equal parts of HF and HNO_3 in two parts water. These specimens were hand polished while the cloth was moistened by the solution.

The alloy numbers in the captions identify the type of material, thus:

Alloy No. 5	Natural Uranium	ORNL Reactor Slugs
" " 6	" "	" " "
" " 7	" "	" " "
" " 8	" "	Special Ingot

Alloy No. 9	6.5% Enriched Uranium	Special Ingot
" " 10	2.7% Enriched Uranium	" "

Legend of Figures

The first number following the figure number is the alloy number. The numbers and letter immediately following the alloy numbers are the specimen numbers. Thus 6A1-129, CS means alloy No. 6A-1, metallographic specimen No. 129, cross section.

Further abbreviations are used as follows:

Ann	=	Annealed at
RM	=	Rolled on 6 in. × 10 in. rolling mill.
HRM	=	Rolled at 290°C to 200°C on hand crank driven rolling mill.
Sw	=	Swaged at 290°C to 200°C in 3/8 in. swaging machine.
W.Dr.	=	Drawn to wire in square wire drawing dies.
LS	=	Longitudinal section
CS	=	Cross section
Percent red	=	Per cent reduction in area after last anneal.
fb	=	Followed by
FC	=	Furnace cooled.

TABLE V

Rockwell Hardness Numbers of Uranium Normal and Enriched Samples

CONDITION OF SAMPLES			NORMAL			ENRICHED WITH 235	
			0	0	0	2.7	6.5
TREATMENT	TEMPERATURE	SIZE	NO.6	NO.7	NO.8	NO.10	NO.9
Annealed	900°C	1.1 in. diam.	B-85	B-89	B-85		
Annealed	900°C	.75 in. diam.	B-77		B-78	B-91	B-93
Annealed	900°C	.50 in. diam.	B-81	B-78		B-92	B-86
Annealed	900°C	.38 in. diam.	B-81		B-82	B-89	B-88
Average			B-81	B-84	B-82	B-91	B-89
Annealed	700°C	.5 in. diam.	B-88	B-89			
Annealed	700°C	.25 in. diam.	B-88				
Annealed	700°C	.21 in. diam.	B-88				
Annealed	625°C	.29 in. diam.			B-89	B-95	B-94
Annealed	625°C	.23 in. diam.	B-92	B-96	B-89	B-95	B-94
Annealed	625°C	.19 in. diam.		B-95			
Annealed	625°C	.15 in. diam.	B-95				
Annealed	625°C	.13 in. diam.	B-94		B-92	B-99	B-98
Annealed	625°C	.12 in. diam.	B-94	B-96		B-100	B-100
Average			B-94	B-96	B-90	B-97	B-96
α-rolled rounds							
26%	300°C	.75 in. diam.	C-35				
32%	300°C	.88 in. diam.	C-28				
43%	300°C	.18 in. diam.	C-32		C-32	C-33	C-30
46%	300°C	.38 in. diam.	C-33				
50%	300°C	.50 in. diam.	C-33				
60%	300°C	.75 in. diam.			C-31	C-36	C-38
Average			C-32		C-32	C-35	C-34

Second Column: Temperature - gives the temperature of annealing and of rolling, swaging and drawing.

TABLE V (Cont' d)

CONDITION OF SAMPLES				NORMAL		ENRICHED WITH 235	
			0	0	0	2.7	6.5
TREATMENT	TEMPERATURE	SIZE	NO.6	NO.7	NO.8	NO.10	NO.9
α-rolled squares							
45%	300°C	.12 in. sq.	C-35				
49%	300°C	.15 in. sq.	C-35				
52%	300°C	.13 in. sq.	C-34				
55%	300°C	.25 in. sq.	C-33				
Average			C-34				
α-swaged 20%, then α-rolled 30%							
44%	300°C	.13 in. sq.			C-33	C-32	C-31
α-swaged							
22%	300°C	.23 in. diam.	C-22				
38%	300°C	.29 in. diam.			C-27	C-27	C-24
35%	300°C	.19 in. diam.			C-24	C-28	C-28
Average			C-22		C-26	C-28	C-26
α-rolled 50%, then drawn 12%							
56%	300-150°C	.12 in. sq.	C-31				
α-rolled 57%, then drawn 7%							
60%	300-150°C	.12 in. sq.	C-35				
Drawn							
10%	150°C	.12 in. sq.				C-30	C-31
10%	150°C	.12 in. sq.				C-32	C-29
10%	150°C	.12 in. sq.				C-30	C-31
15%	150°C	.12 in. sq.				C-32	C-33
20%	150°C	.12 in. sq.	C-33	C-30			
37%	150°C	.12 in. sq.	C-33				
Average			C-33	C-30		C-31	C-31

TABLE VI

WIRE LOT NO.	DIMENSION (inches)	REDUCTION IN AREA (Percent)	TENSILE STRENGTH (psi)	FRACTURE STRESS (psi)	EXTENSION AND GAGE LENGTH (inches)	AMOUNT OF COLD WORK SINCE LAST ANNEAL			ANNEALING TIME AND TEMPERATURE	ROCKWELL HARDNESS NUMBER
						BY HAND ROLLING MILL (Percent)	BY WIRE DRAWING (Percent)	TOTAL REDUCTION (Percent)		
6B1	.1182 .1170	1.8	153,000	154,000	3.1% in 1 2.3% in 2	0	21	21		C-33
6B1	.1175 .1140	5.1	108,300	113,000*				0	2 hrs 625°C	B-94
6B1	.1165		138,000		4.7% in 2			0	2 hrs 625°C	
6B2	.1190 .1175		144,800	146,000*		0	37	37		C-33
6B2	.1263		125,000				37	37		
7B	.1182 .1155	4.0	138,000	142,000	5.0% in 2		20	20		C-30
7B	.117 .111	10.	125,000	135,000	6.0% in 2			0	2 hrs 625°C	
7B	.1175 .1142	5.6	125,600	131,900	6.0% in 2			0	2 hrs 625°C	B-96
7A2	.1185 .1120	10.7	149,500	163,500**	6.0% in 2	35.5	7.5	40		C-30
7A2	.1185 .116	4.1	153,500	160,000	2.4% in 2	35.5	7.5	40		
7A1	.1188 .1174	2.4	171,000	172,000	3.1% in 2	54	5	56.5		C-35
7A1	.1175 .1065	10.5	120,000	144,500	27% in 2			0	2 hrs 625°C	B-97

TABLE VI (Cont'd)

WIRE LOT NO.	DIMENSION (inches)	REDUCTION IN AREA (Percent)	TENSILE STRENGTH (psi)	FRACTURE STRESS (psi)	EXTENSION AND GAGE LENGTH (inches)	AMOUNT OF COLD WORK SINCE LAST ANNEAL: BY HAND ROLLING MILL (Percent)	BY WIRE DRAWING (Percent)	TOTAL REDUCTION (Percent)	ANNEALING TIME AND TEMPERATURE	ROCKWELL HARDNESS NUMBER
7A1	.118 .110	12.9	160,000 112,500	128,000	12.5% in ½ 13.0% in 1 12.0% in 2			0	2 hrs 625°C	B-97
7A2	.1185 .113	9.1	106,000 112,200	124,000	**			0	2 hrs 625°C	B-96
9.1	.1185 .100	15.6	133,500	177,000	12.7% in 1.4 18.0% in 2	0	10.1	10.1		C-31
9.2	.1185 .108	8.9	130,500	171,500	15.6% in 2	0	10.1	10.1		C-31
9.4	.119 .105	22.2	144,000	180,000	22.5% in ½ 22.0% in 1 21.0% in 1½ 20.0% in 2	0	15	15		C-33
9.4	.119 .111 × 113	11.3	118,000	132,000	25.0% in ½ 18.75% in 1 20.8% in 1½ 18.75 in 2			0	3 hrs 625°C	B-98
10.13*	.1185 .1130	8.9	139,000	149,000	6.5% in ½ 9.4% in 1 8.8% in 2	0	10.1	10.1		C-32
						Dark spot, perhaps oxidized crack, showed up in corner of fracture				
10.11**	.1188 .1150	6.4	142,800	150,000	2.5% in 2	0	10.1	10.1		C-32
10.21 after fracture displayed longitudinal split, due to overwork										
10.12	.119 .114 Small inside crack	9.2	130,500	140,500	9.3% in 1 8.3% in 1½	0			3 hrs 625°C	B-100

TABLE VI (Cont'd)

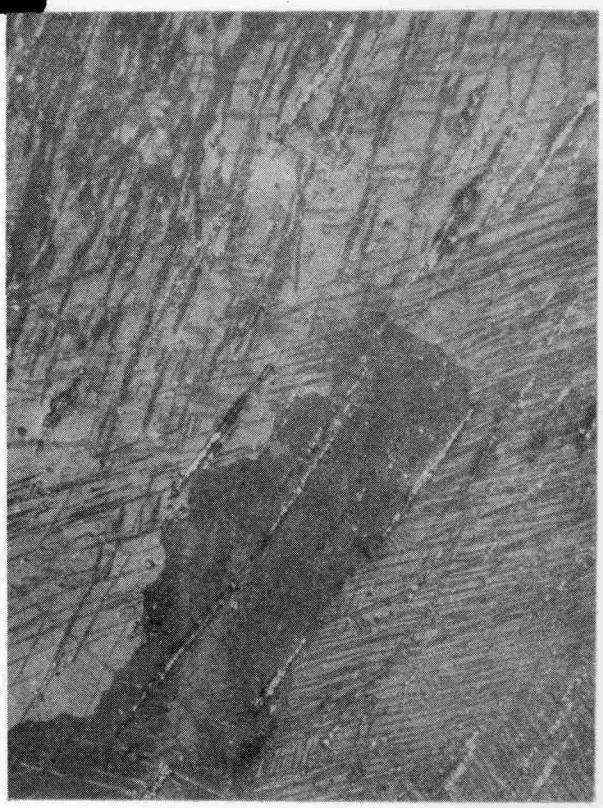
WIRE LOT NO.	DIMENSION (inches)	REDUCTION IN AREA (Percent)	TENSILE STRENGTH (psi)	FRACTURE STRESS (psi)	EXTENSION AND GAGE LENGTH (inches)	AMOUNT OF COLD WORK SINCE LAST ANNEAL			ANNEALING TIME AND TEMPERATURE	ROCKWELL HARDNESS NUMBER
						BY HAND ROLLING MILL (Percent)	BY WIRE DRAWING (Percent)	TOTAL REDUCTION (percent)		
10.21	.1185		137,800		18.6% in ½ 15.6% in 1	0	10.1	10.1		C-32
	.113	8.9		146,000	12.5% in 1½					
10.21 after fracture displayed a narrow longitudinal split										
10.22	.119		126,000		18.75% in 1		10.1	10.1		C-28
	.112	12.		142,400	13.4% in 1½ 13.5% in 2					
10.31	.1185		115,500		28.0% in ½					B-100
	.1185		123,200		27.0% in 1				3 hrs 625°C	
	.105	21.5		155,000	25.5% in 1½ 25.0% in 2					
10.4	.119		174,000		9.5% in 1½	0	15	15		C-32
	.1145	7.5		182,000	6.5% in 1 4.2% in 1½ 3.9% in 2					
10.4	.119	24.	127,500	166,000	18.75% in ½ 15.9% in 1					B-99
	.101 × 1065				16.3% in 1½ 15.6% in 2				3 hrs 625°C	

*Broke in grips
**Broke outside gage marks

[redacted]

Y-71

Fig. 1
5A-81, LS. Ann 900°C 2 hrs fb RM 1-1/16 in. diam to 9/16 in. diam (72 percent red).

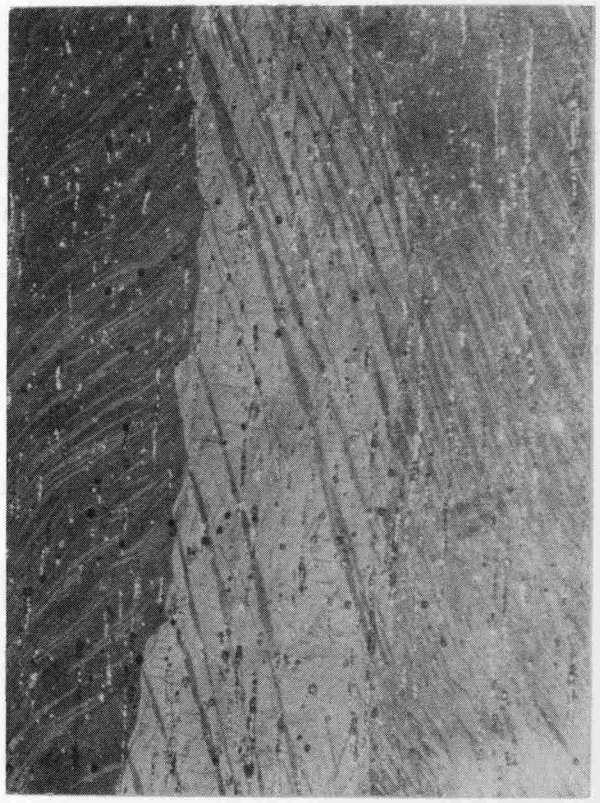


Y-73

Fig. 2
5A-111, LS. HRM .25 in. diam to .16 in. sq (50 percent red) fb Ann 900°C. FC.

Y-622

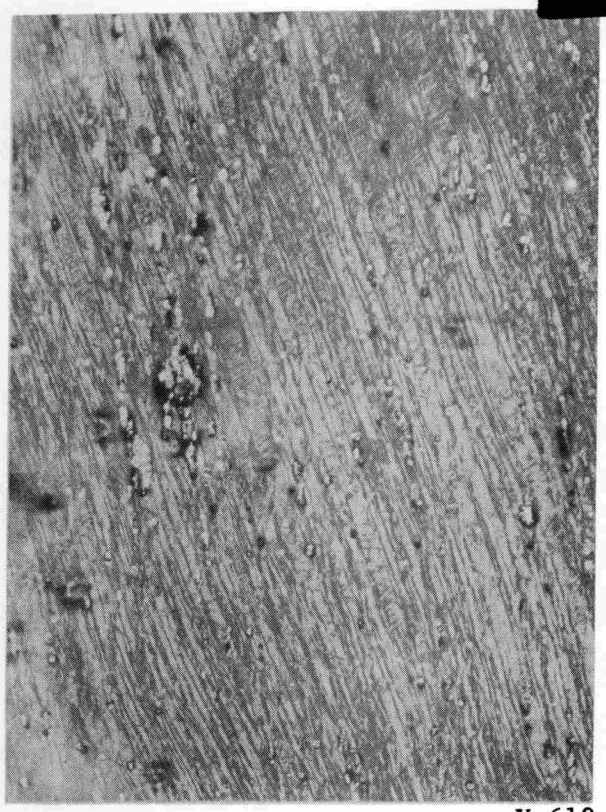
Fig. 3
6Al-129, LS. Ann 900°C fb HRM 3/8 in. diam to 7/32 in. diam (66 percent red).



Y-652

Fig. 4
6-130, LS. Ann 900°C 15 min. FC fb Sw 3/8 in. to .29 in. diam (40 percent red).

[redacted]



Y-619

Fig. 5
7-119, LS. Ann 900°C 40 min fb RM 1-1/16 in. diam to 3/4 in. diam (50 percent red).

Y-629

Fig. 6
7-128, LS. Ann 900°C 30 min fb RM ½ in. diam to 3/8 in. diam (44 percent red).

Y-507

Fig. 7
9-251, LS. Ann 900°C 3 hrs fb RM .5 in. diam to .365 in. diam (46.5 percent red).

Y-505

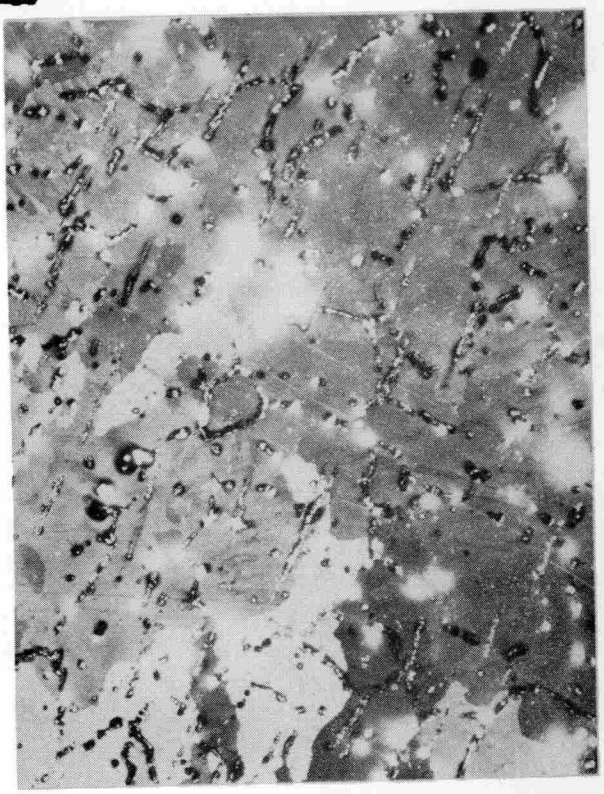
Fig. 8
9-257, CS. Ann 900°C 2 hrs fb Sw 365 in. diam to .286 in. diam (38 percent red).

[redacted]

Y-506

Fig. 9

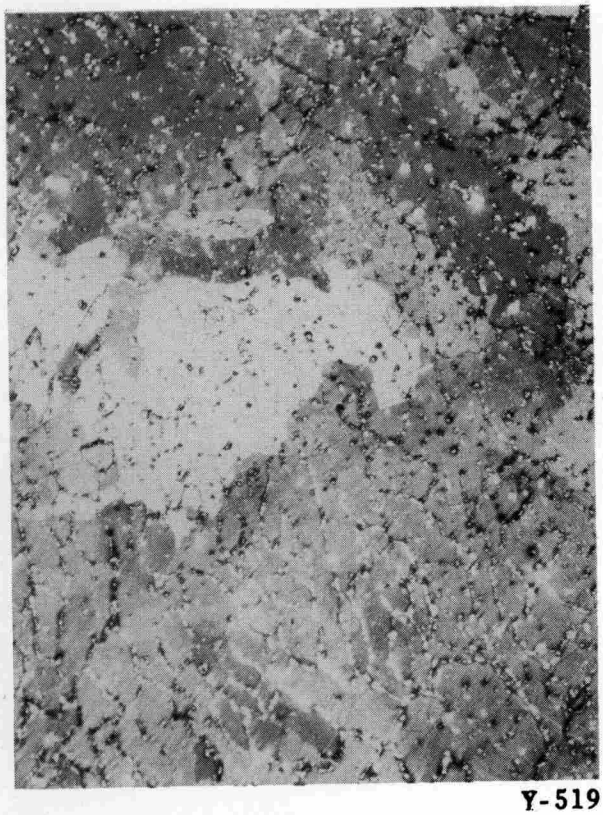
9-257, LS. Ann 900°C 2 hrs fb Sw .365 in. diam to .286 in. diam (38 percent red).



Y-520

Fig. 10

10-255, LS. RM .48 in. diam to .34 in. diam (50 percent red) fb Ann 900°C 2 hrs.



Y-519

Fig. 11

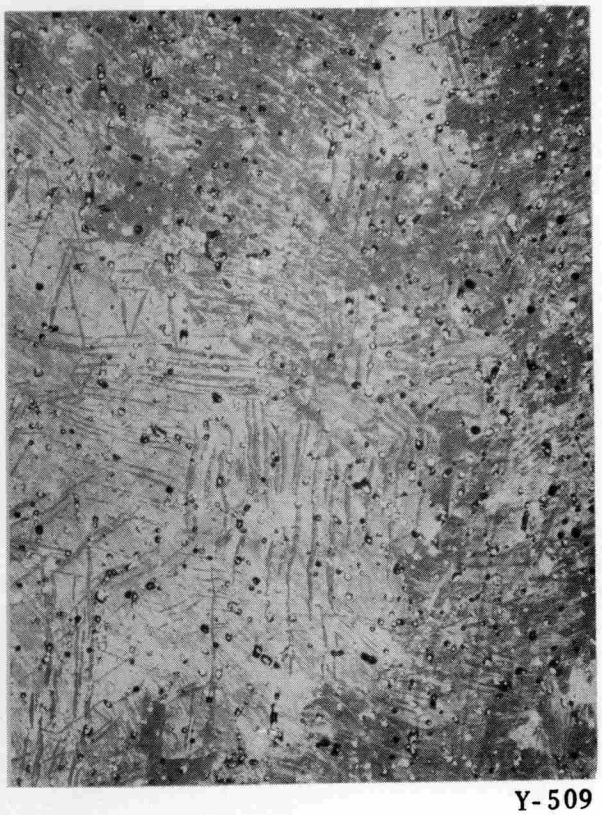
10-255, CS. RM .48 in. diam to .34 in. diam (50 percent red) fb Ann 900°C 2 hrs.

Y-502

Fig. 12

10-250, LS. Ann 900°C 30 min fb RM 48 in. diam to .34 in. diam (50 percent red).

[redacted]

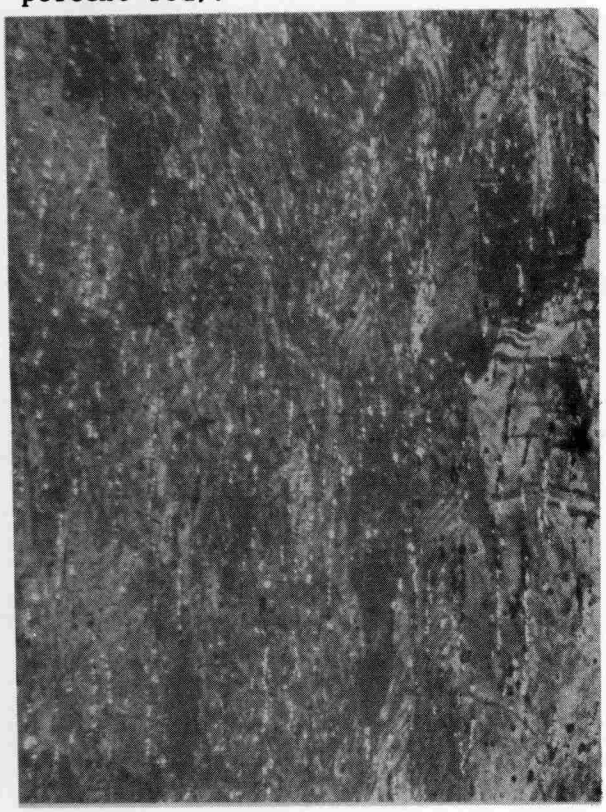


Y-509

Fig. 13
10-258, CS. Ann 900°C 2 hrs fb Sw .34 in. diam to .287 in. diam (28 percent red).

Y-510

Fig. 14
10-258, LS. Ann 900°C 2 hrs fb Sw .340 in. diam to .287 in. diam (28 percent red).



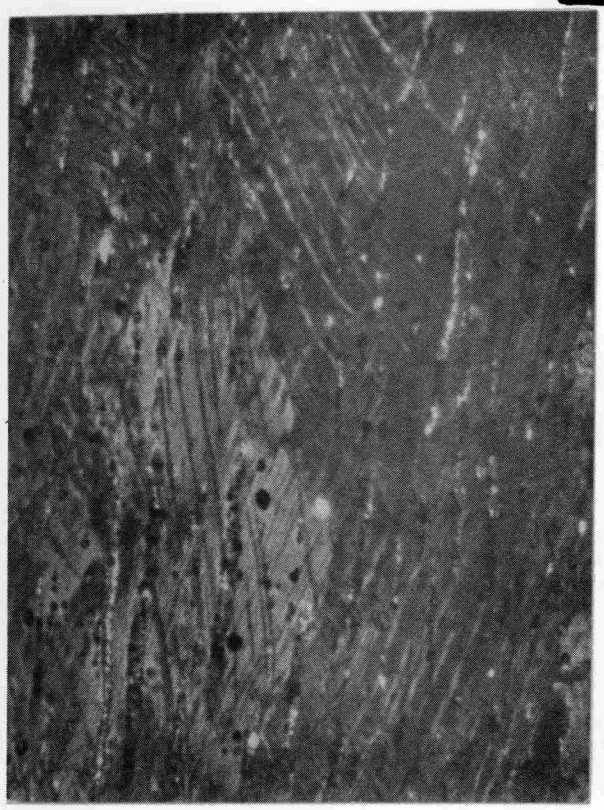
Y-155

Fig. 15
6B2-156, LS. Ann 700°C 30 min fb HRM .21 in. sq to .15 in. sq (50 percent red).

Y-625

Fig. 16
6B1-155, LS. Ann 700°C 30 min fb Sw .26 in. diam to .23 in. diam (21 percent red).

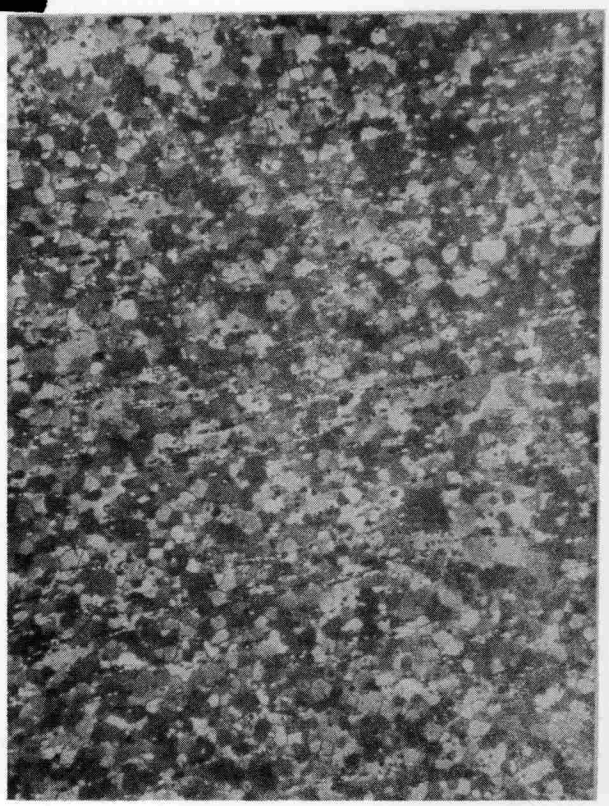
[redacted]



Y-136

Fig. 17

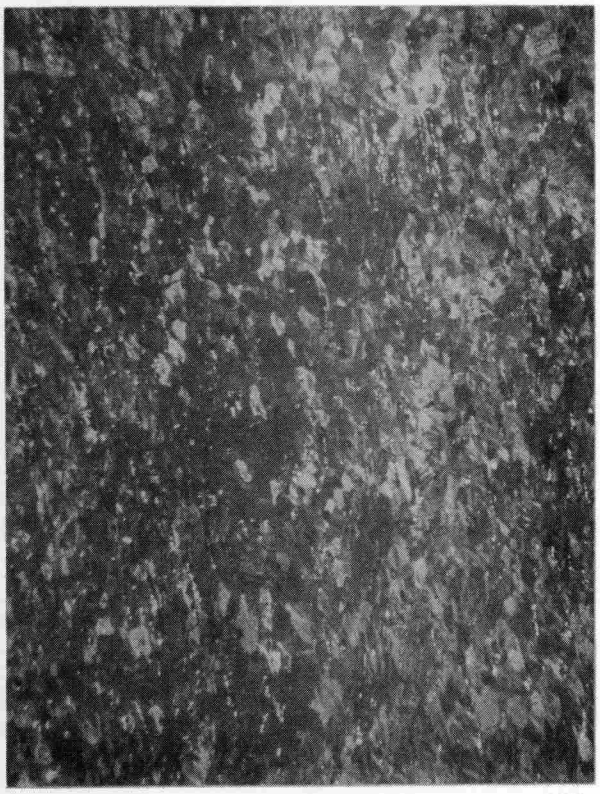
7-209, LS. Ann 700°C 2 hrs fb HRM .281 in. sq to .153 in. sq (70 percent red).



Y-148

Fig. 18

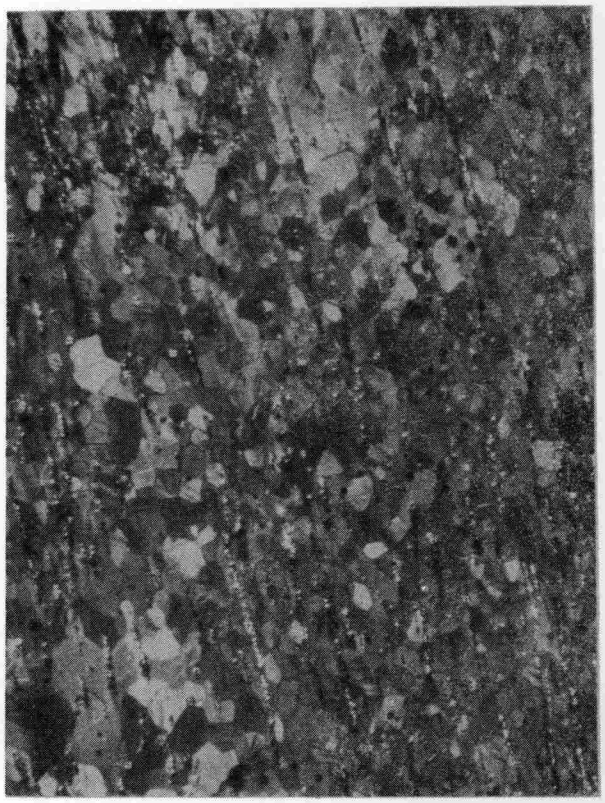
6B1-202, LS. HRM .229 in. sq to .133 in. sq (66 percent red) fb Ann 625°C 3 hrs.



Y-153

Fig. 19

6B2-144, LS. Ann 625°C 16 hrs fb HRM 9/32 in. diam to 7/32 in. diam (40 percent red).

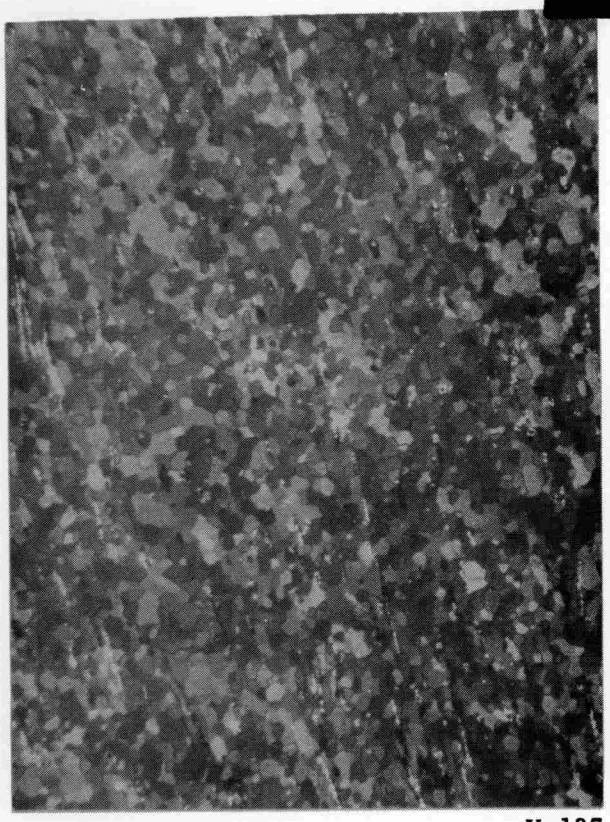


Y-158

Fig. 20

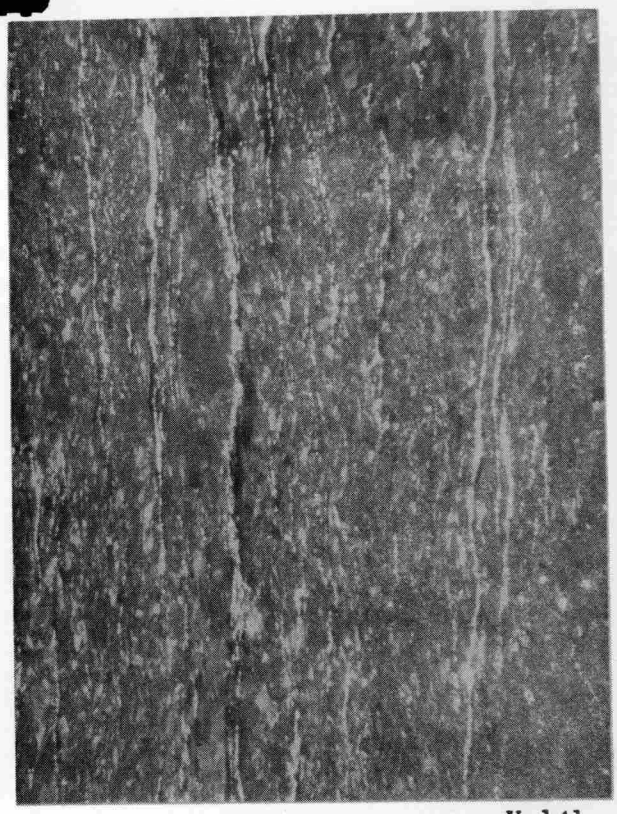
6B1-143, LS. Ann 625°C 16 hrs fb Sw .289 in. diam to .258 in. diam (20 percent red).

[redacted]



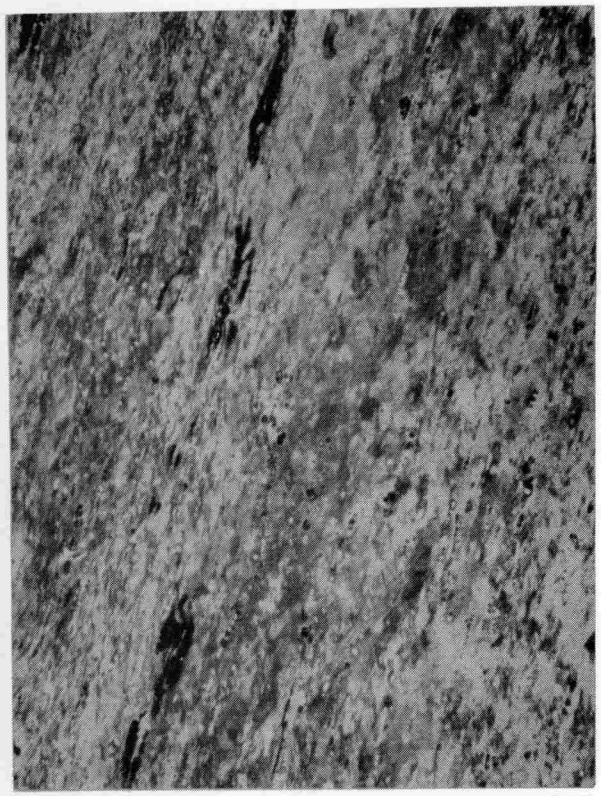
Y-137

Fig. 21
7-208, LS. HRM 9/32 in. sq to .153 in. sq (70 percent red) fb Ann 625° C 3 hrs.



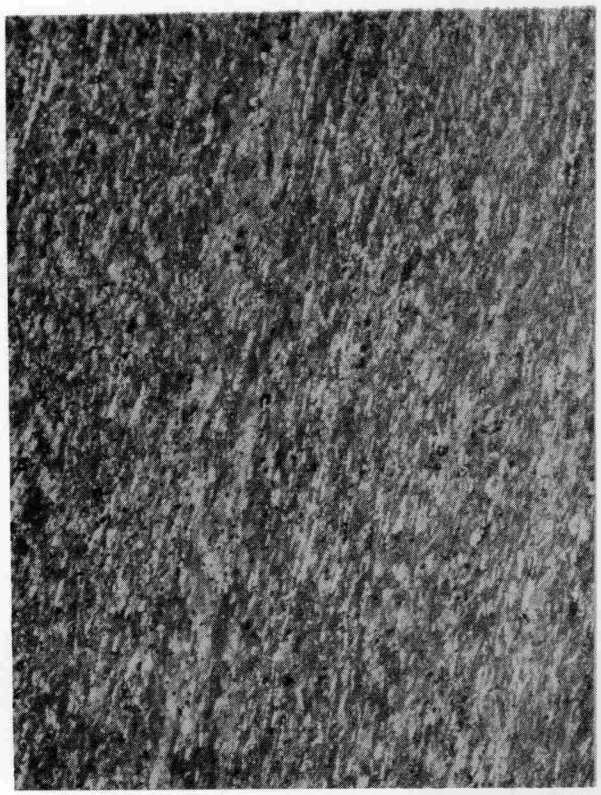
Y-141

Fig. 22
7-207, LS. Ann 625°C 3 hrs fb HRM .18 in. sq to .13 in. sq (48 percent red).



Y-1037

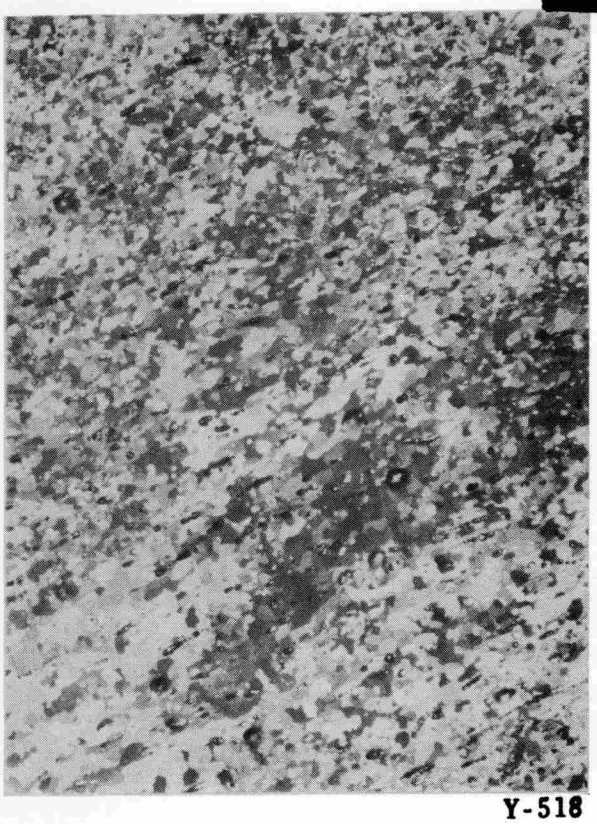
Fig. 23
9-297, LS. Ann 625°C 3 hrs fb Sw .243 in. diam to .182 in. diam fb HRM .182 in. diam to .132 in. sq fb W.Dr. .132 in. sq to .129 in. sq (72 percent red).



Y-532

Fig. 24
9-275, LS. Ann 625°C 3 hrs. Sw .193 in. diam to .162 in. diam fb HRM .162 in. sq to .125 in. sq (58 percent red).

[redacted]



Y-518

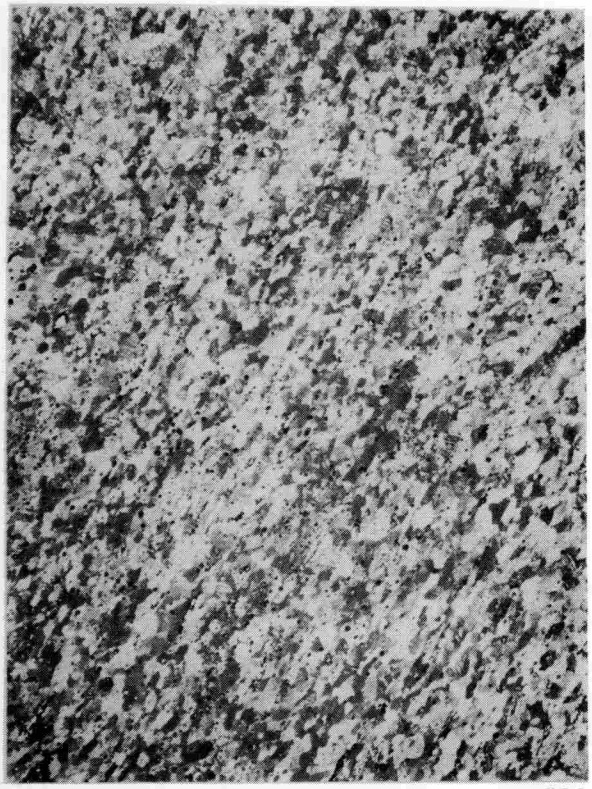
Fig. 25

9-267, LS. Sw 286 in. diam to .193 in. diam (54 percent red) fb Ann 625°C 3 hrs.

Y-521

Fig. 26

9-311, LS. Ann 625°C 3 hrs fb W.Dr. .129 in. sq to .119 in. sq (15 percent red). Large grains due to overheating in die.



Y-529

Fig. 27

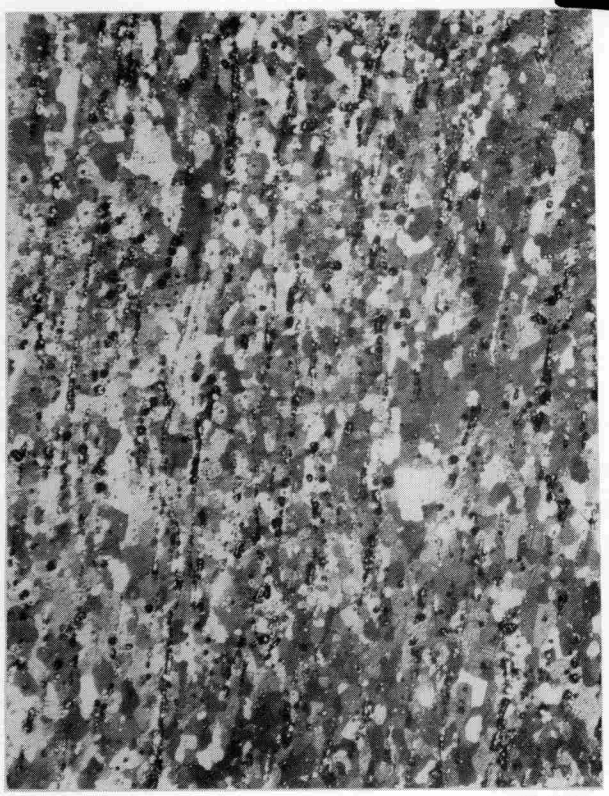
9.2-277, LS. Ann 625°C 3 hrs fb W.Dr. .125 in. sq to .1185 in. sq (10 percent red).

Y-499

Fig. 28

10-274, LS. Ann 625°C 3 hrs fb Sw .193 in. diam to .162 in. diam fb HRM .162 in. diam to .125 in. sq (58 percent red).

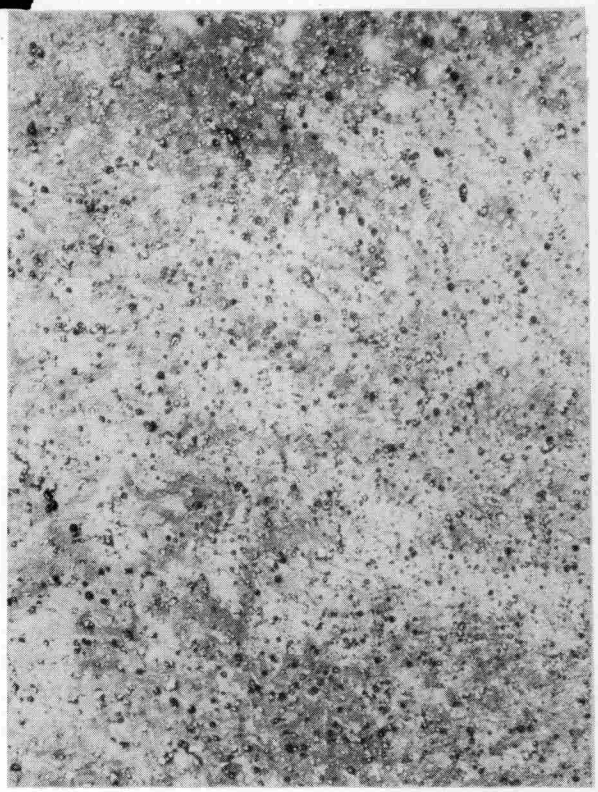
[redacted]



Y-523

Fig. 29

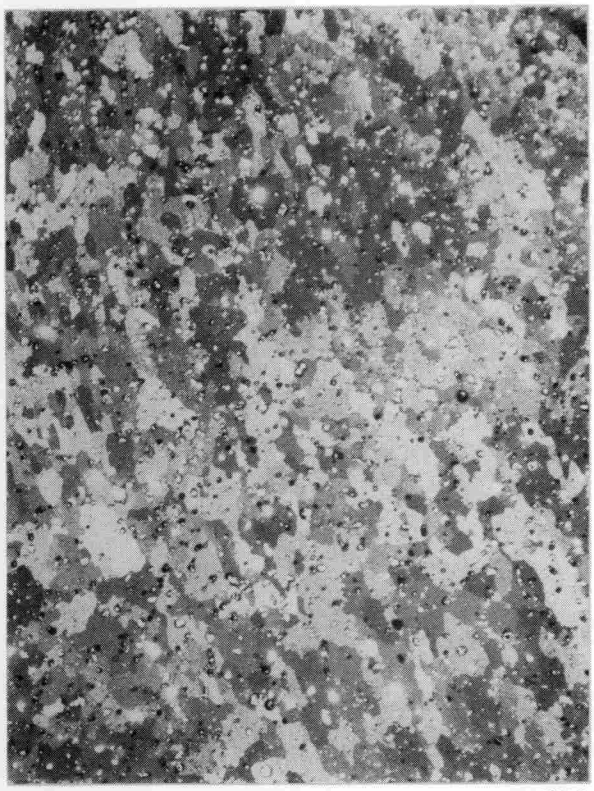
10-268, LS. Sw .287 in. diam to .193 in. diam (54 percent red) fb Ann 625°C 3 hrs.



Y-526

Fig. 30

10-265, CS. Ann 625°C 2 hrs fb Sw .287 in. diam to .193 in. diam (54 percent red).



Y-503

Fig. 31

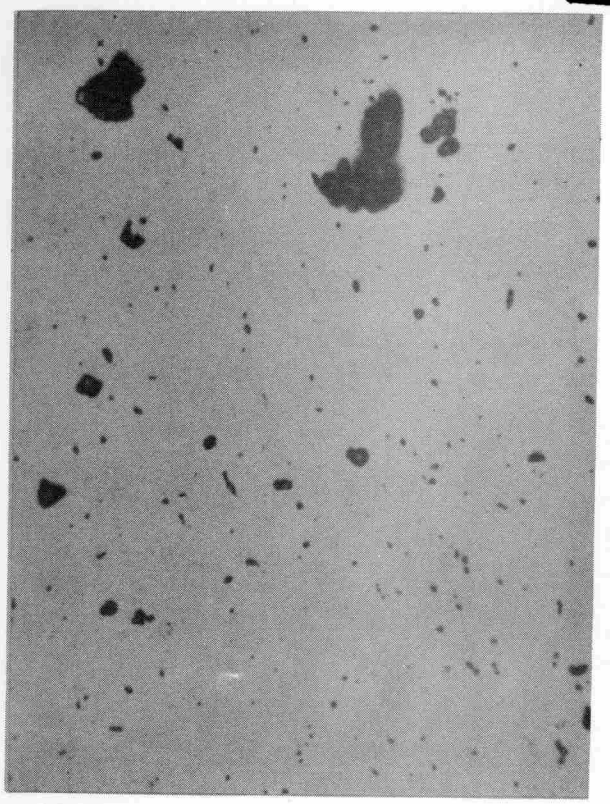
10-261, CS. Sw .340 in. diam to .287 in. diam (28 percent red) fb Ann 625°C 2 hrs.

Y-496

Fig. 32

10.1-278, LS. Ann 625°C 3 hrs fb W. Dr. .125 in. sq to .1185 in. sq (10 percent red). Overheated during wire drawing.

[redacted]

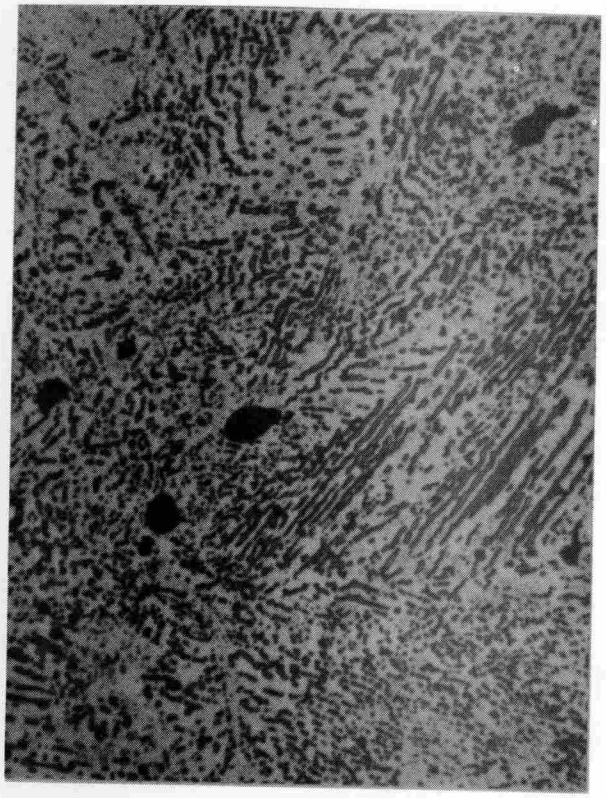


Y-424

Fig. 33
7-120, CS. Ann 900°C 40 min fb RM .71 in. diam to .365 in. diam (74 percent red) fb Ann 900°C 2 hrs x 750.

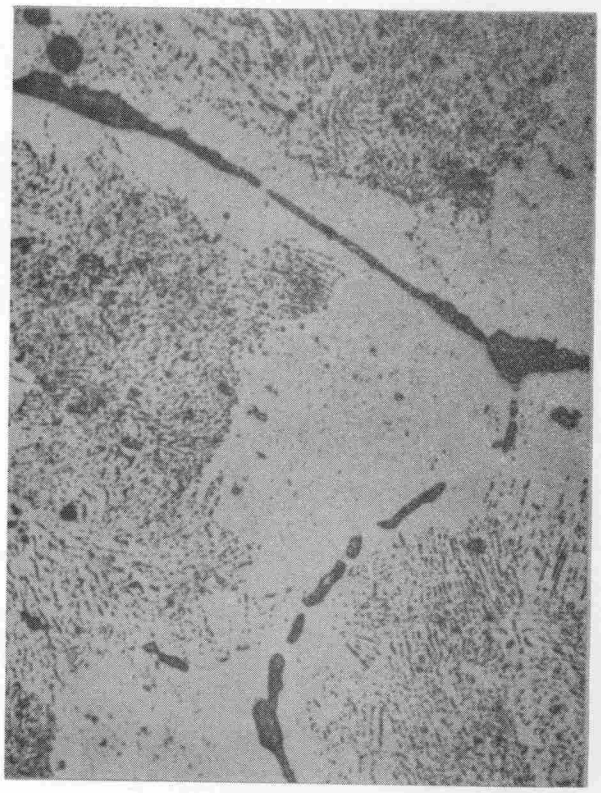
Y-413

Fig. 34
8-253, LS. RM .71 in. diam to .365 in. diam (74 percent red) fb Ann 900°C 2 hrs x 750.



Y-416

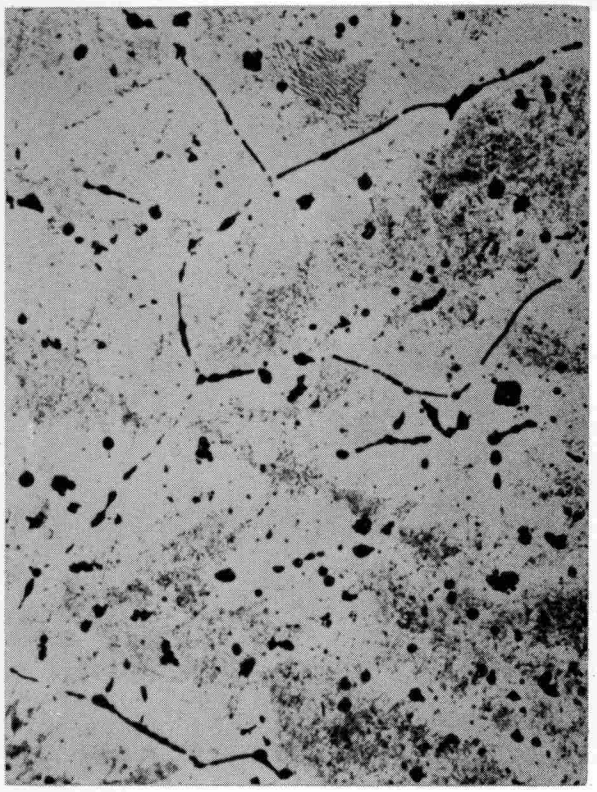
Fig. 35
9-254, CS. RM .5 in. diam to .365 in. diam (47 percent red) fb Ann 900°C 2 hrs.



Y-414

Fig. 36
10-255, CS. RM .478 in. diam to .340 in. diam (50 percent red) fb Ann 900°C 2 hrs x 750.

[redacted]



Y-415

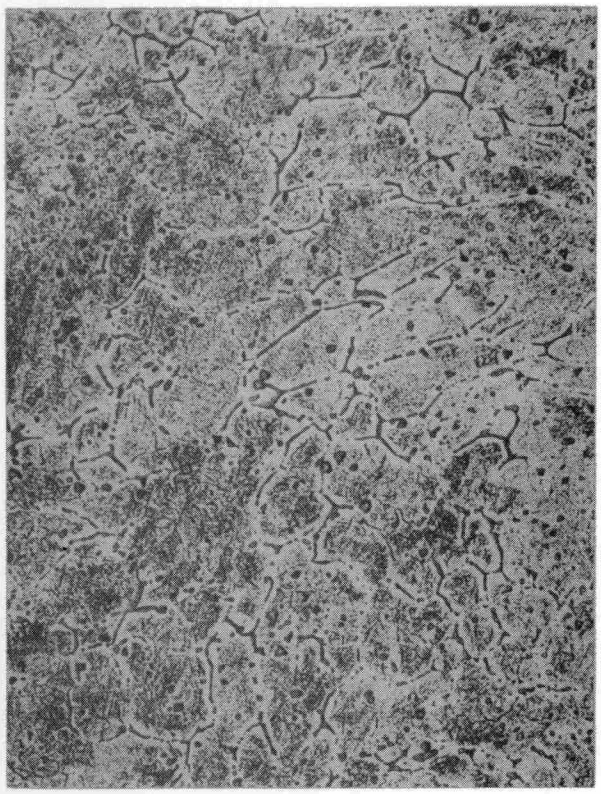
Fig. 37

10-255, CS. RM .478 in. diam to .340 in. diam (50 percent red) fb Ann 900°C 2 hrs x 250.

Y-565

Fig. 38

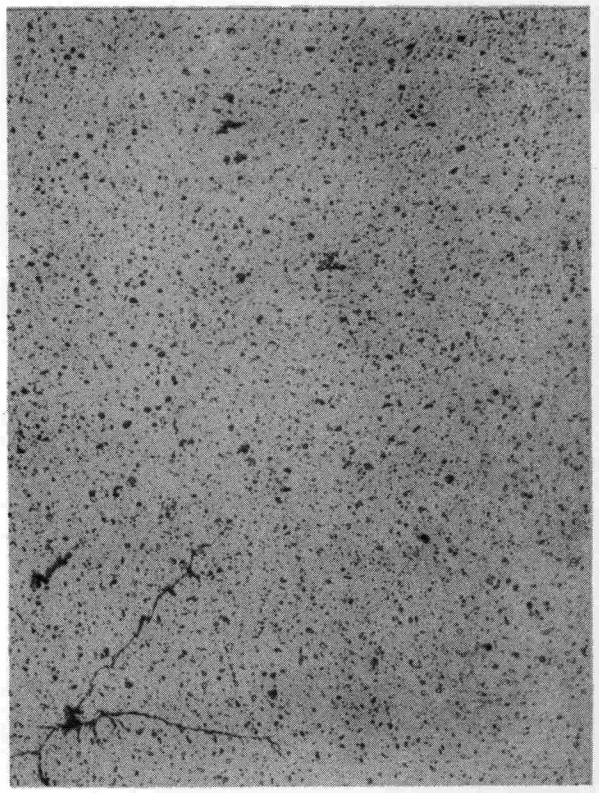
10-250, LS. Ann 900°C 30 min fb RM .48 in. diam to .34 in. diam (50 percent red) x 100.



Y-564

Fig. 39

10-250, CS. Ann 900°C 30 min fb RM .48 in. diam to .34 in. diam (50 percent red) x 100.

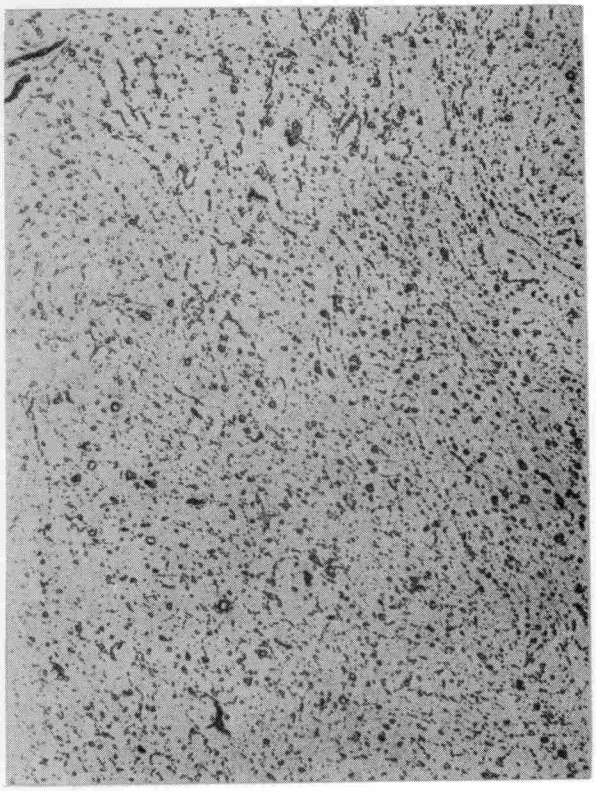


Y-560

Fig. 40

10-280, CS. Ann 625°C 3 hrs fb Sw .193 in. diam to .162 in. diam fb HRM .162 in. diam to .125 in. sq (58 percent red) X-100.

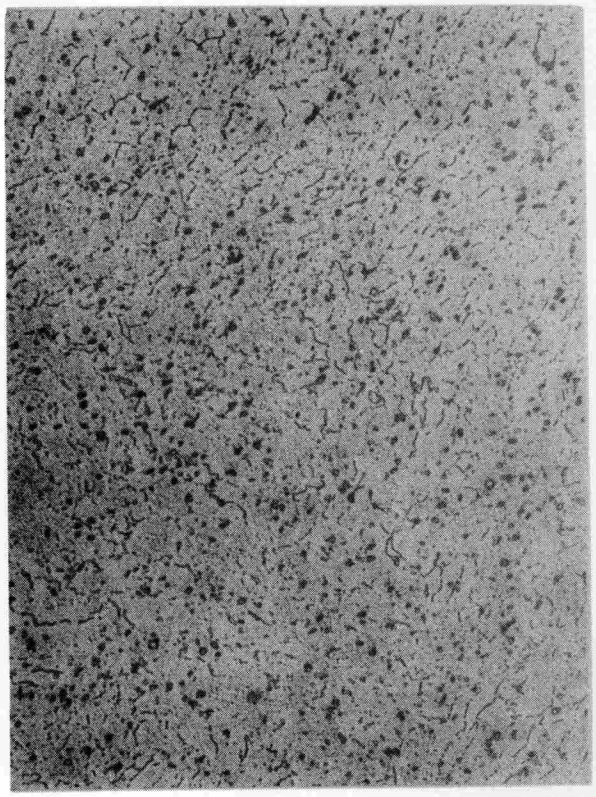
[redacted]



Y-561

Fig. 41

10-282, CS. Ann 625°C 3 hrs fb Sw .193 in. diam to .162 in. diam fb HRM .162 in. diam to .125 in. sq (58 percent red) X-100.



Y-563

Fig. 42

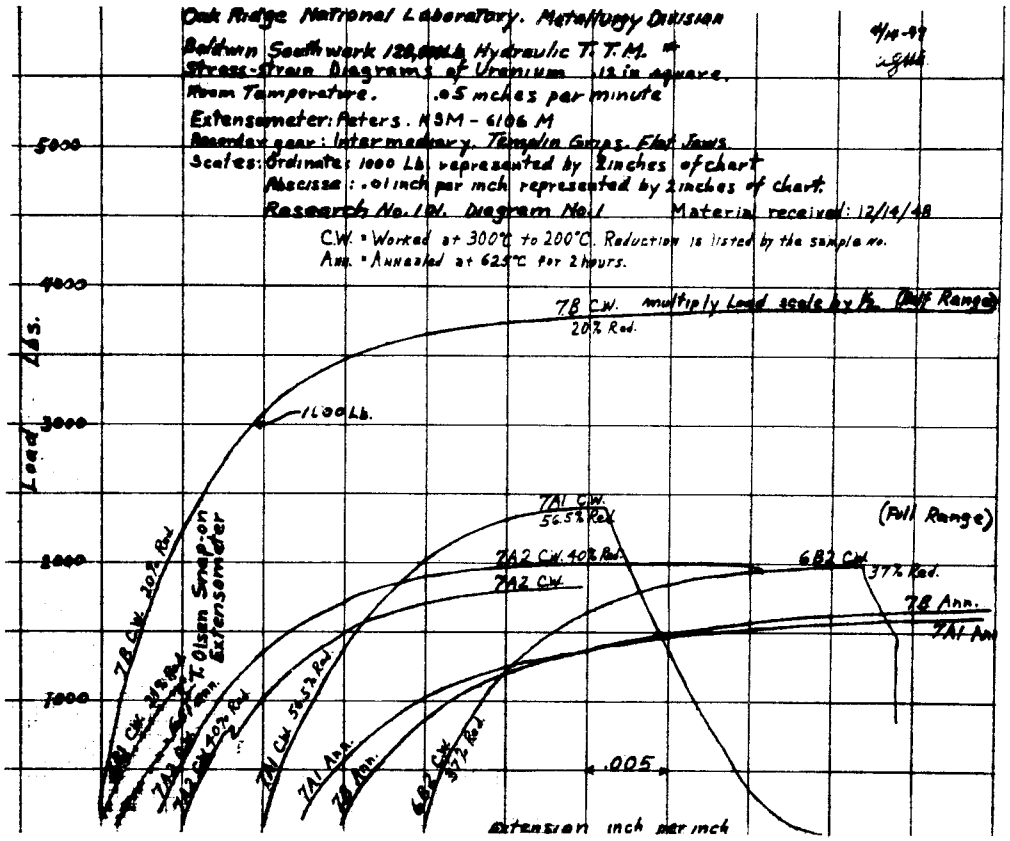
10.22-285, CS. Ann 625°C 3 hrs fb Sw .243 in. diam to .182 in. diam (44 percent red).

Y-562

Fig. 43

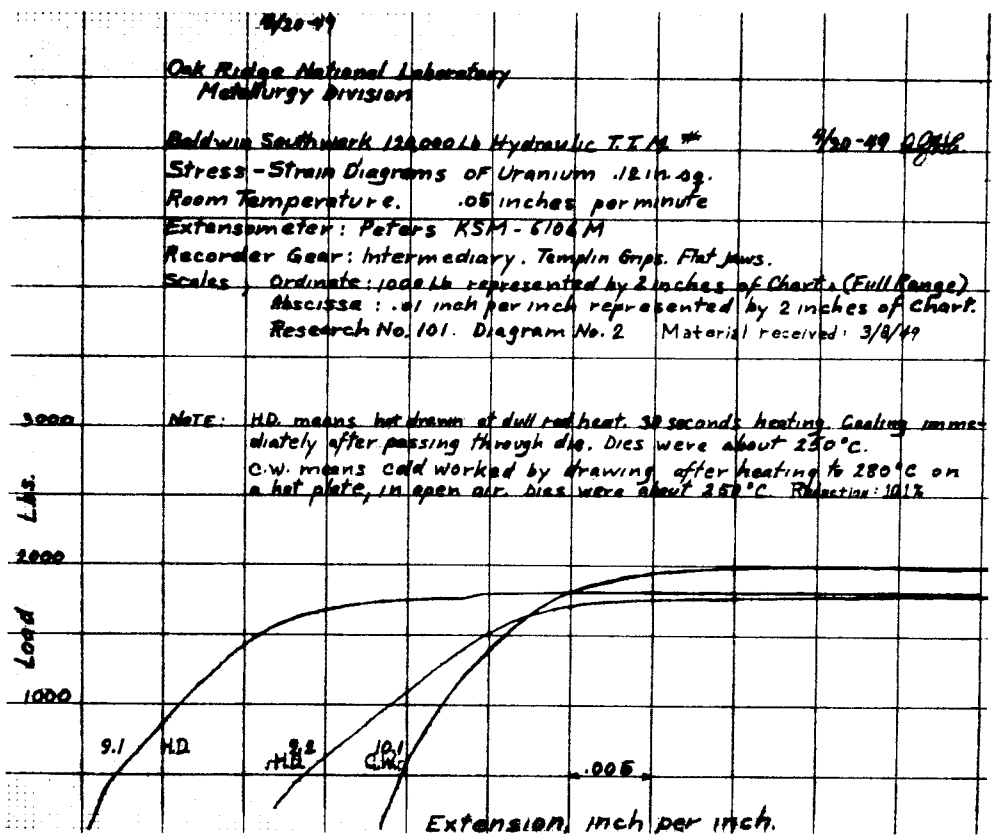
10-312, LS. Ann 625°C 3 hrs fb W.Dr. .129 in. sq to .1185 in. sq (15 percent red).

[redacted]



Y-393

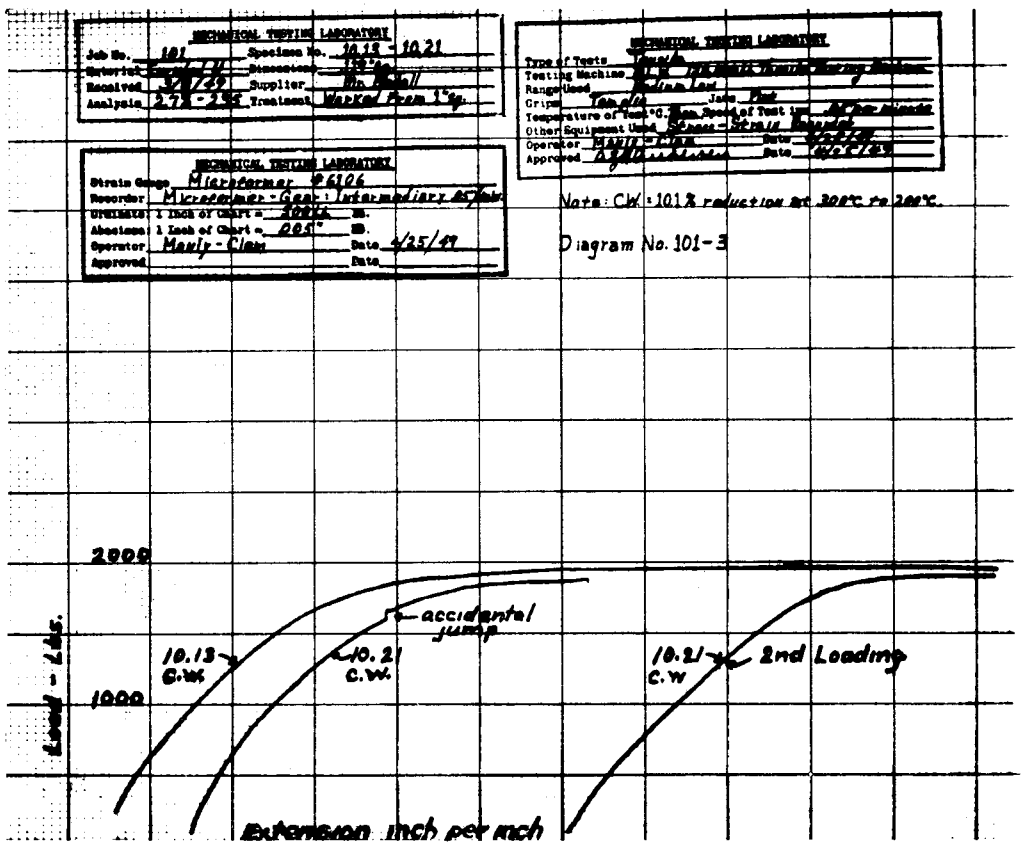
Fig. 44



Y-392

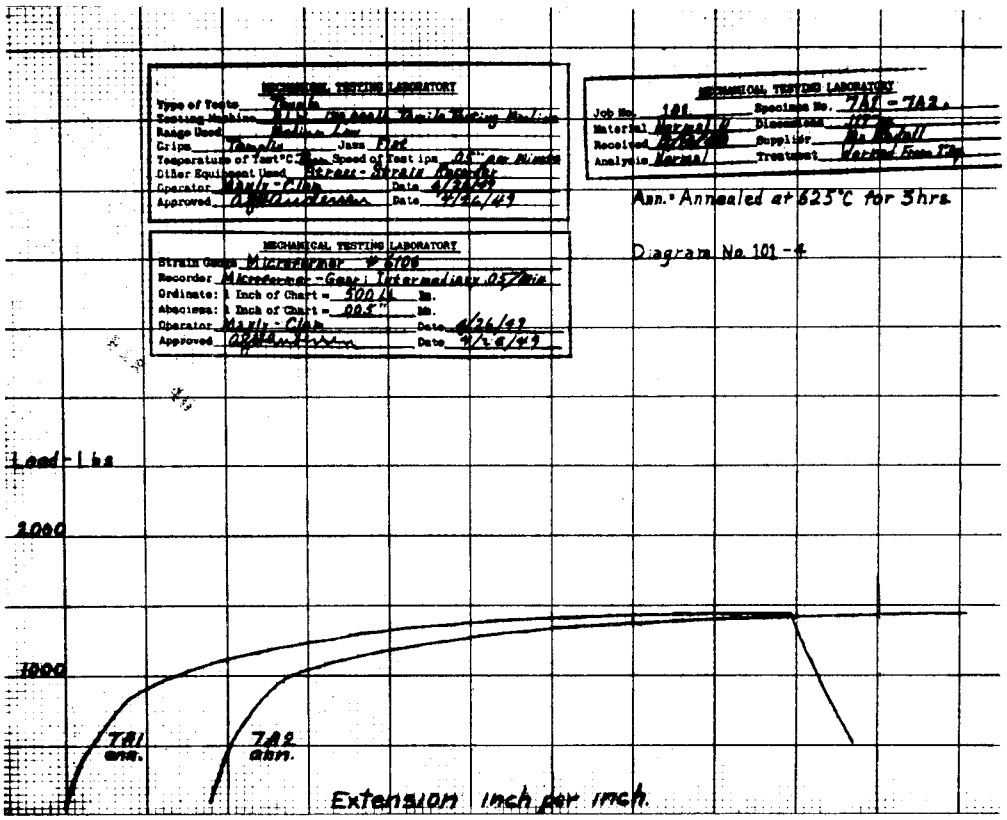
Fig. 45

[redacted]



Y-394

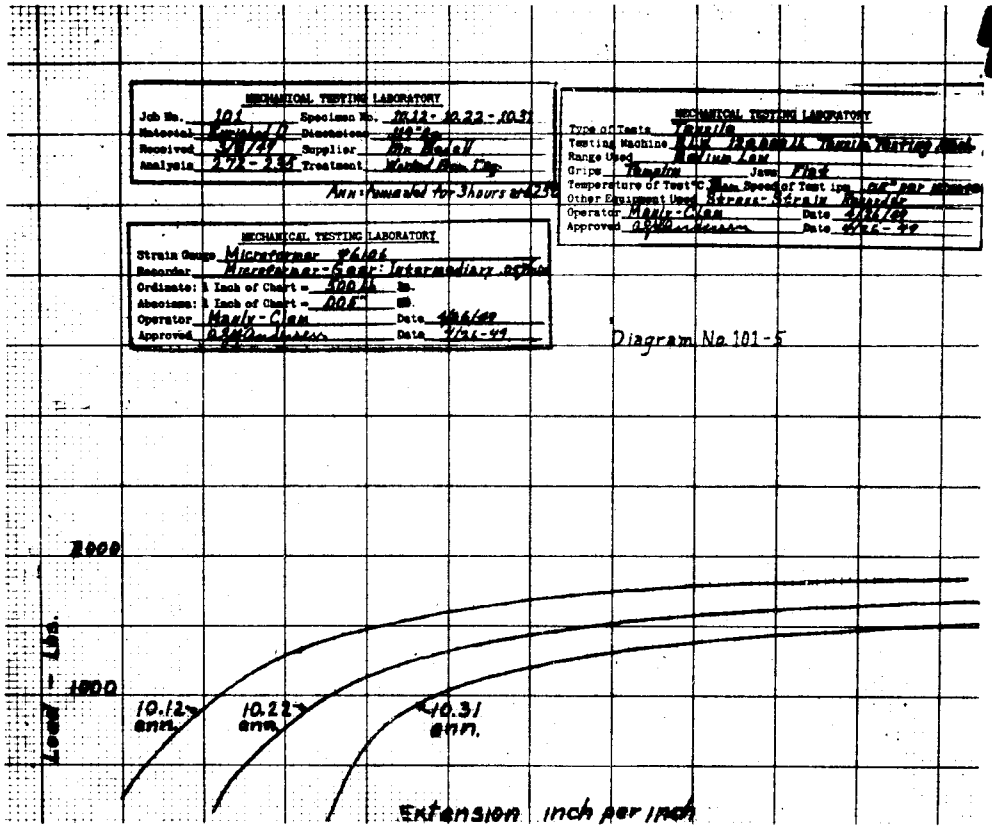
Fig. 46



Y-419

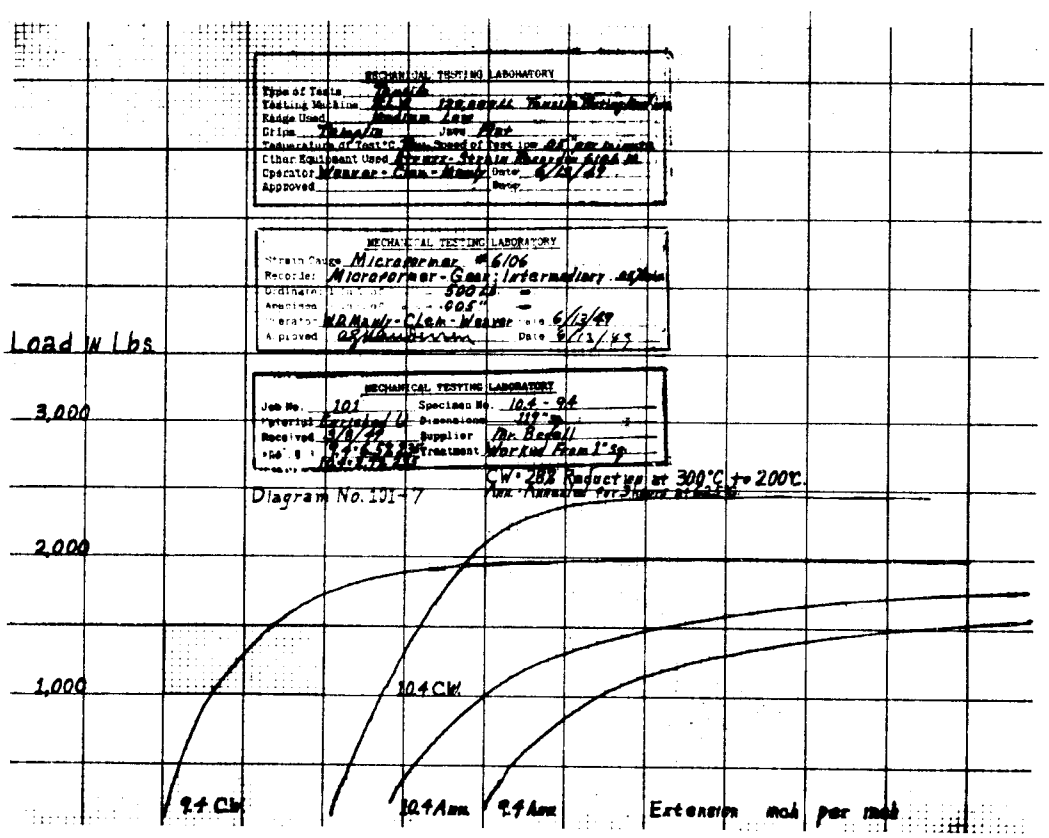
Fig. 47

[redacted]



Y-391

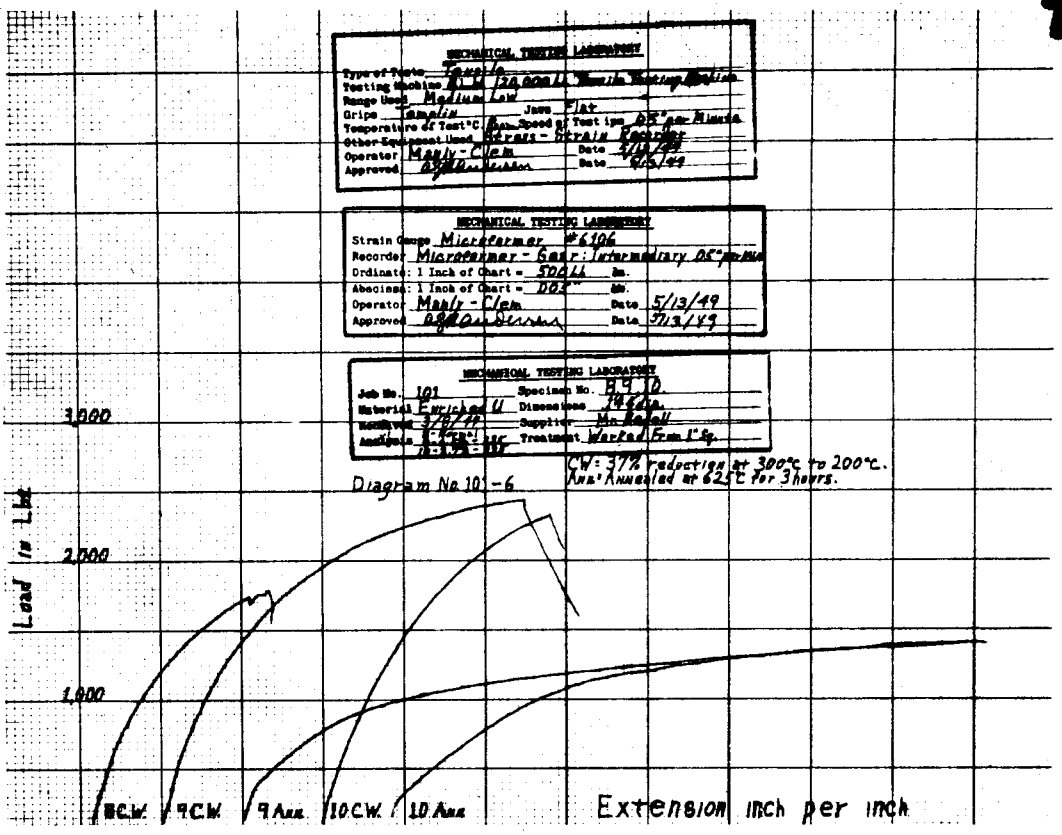
Fig. 48



Y-418

Fig. 49

[redacted]



Y-420

Fig. 50