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Argonne National Laboratory

THE FABRICATION OF CERTAIN JACKETED URANIUM HELICES

by

F. L. Yaggee

ANL-5690
Metallurgy and Ceramics

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PREFACE

The helical elements described in this report were fabricated for special purpose items, namely, the Doppler Experiments conducted in the ZPR-III facility. These helices were not intended for, and should not be used, in other in-pile tests, particularly where the test conditions depart materially from those of the Doppler Experiments.

INTRODUCTION

The purpose of this report is to present, in a descriptive manner, the techniques used in the fabrication of certain jacketed, uranium helical elements, commonly referred to as the Doppler Helices. Briefly, these elements consisted of a 1/8" diameter x 12 ft long uranium core completely enclosed within a 0.005"-0.006" thick stainless steel or nickel jacket and wound into a helix or spring having a prescribed inside diameter and spacing between turns. The mechanically drawn-on jacket was separated from the metallic uranium core by a thin, intervening layer of uranium oxide.

The so-called Doppler Experiments were conducted in Argonne's ZPR-III facility during the periods October 16-25 and November 14-16, 1956. These experiments were designed and performed by members of the ANL Reactor Engineering Division for the purpose of detecting and measuring the magnitude of the reactivity change occurring in a fast neutron assembly as a result of temperature effects manifested in the fissile material itself. The helices served as the test specimens upon which reactivity measurements were made. Since the ZPR-III assembly is essentially a zero power machine, artificial means were used to induce the necessary temperature effect into the test specimens. More precisely, the individual helices were thermally cycled through a recorded temperature range by the alternate passage of a large electric current through the uranium core, followed by the flow of an inert gas over the heated specimen. Currents of the order of 125-130 amp (current density $\sim$1.00-1.04 amp/cir. mil) were used during the heating cycle; helium at approximately dry-ice temperature served as the cooling medium.

The presentation and interpretation of data obtained from these experiments into the physics of fast reactor systems is outside the intended scope of this report. This information is the subject of another report by the authors of the Doppler Experiments.(1)

SPECIFICATIONS

Specifications delineating the dimensional and material requirements for the helices are given below as formulated by W. Y. Kato of the ANL Reactor Engineering Division. In addition to these requirements, it was requested that the metallurgical condition of the uranium core be such as to exhibit as nearly isotropic thermal expansion as possible during several hundred cycles in the temperature range 20°C-300°C.

Core	
Material	Unalloyed Uranium Enriched and Natural
Diameter	0.125"-0.126"
Density	As high as possible.
Outer Jacket	
Material	Type 304 Stainless Steel or Nickel
Thickness	Approx. 0.005"
Helix Dimensions	
Inside Diameter	1.0"
Number of Turns	30 - 40
Spacing between Turns	1/16"

FABRICATING SEQUENCE

The present fabrication of helical elements was accomplished in a conventional manner by rolling, swaging, machining and drawing, with certain variations in technique to accommodate the known peculiarities of uranium. Most of the difficulties encountered were directly attributable to the uniqueness of the item being fabricated, particularly with reference to geometry. For example, established techniques for the hot working and heat treating of uranium rods having a ratio of diameter to length of 1:10 (0.600" dia. x $6\frac{1}{2}$" long) are not necessarily suited for long, thin rods whose diameters are less than 0.200" and whose lengths are in excess of 3 ft (ratio of diameter to length $\geq$ 1:180). The special techniques described herein were devised to circumvent these fabricating difficulties in the shortest possible time and without the benefit of development work. Although they proved to be adequate in producing the desired product, no claim is made that they are the only workable techniques for such a fabrication, nor would they necessarily be applicable to a volume production process.

A. Melting and Casting

The unalloyed uranium core material, enriched and natural uranium, was induction melted in thoria ceramics and gravity cast into a single cavity, split graphite mold. A vacuum of the order of 4×10^{-4} mm Hg was maintained at a pouring temperature of 1400-1450°C. Carbon pickup from the mold was minimized by the application of a sprayed and dried thoria wash to the mold cavity.

The cast billet size in each of four castings, two each of enriched and of natural uranium, was 5/8" diameter x $6\frac{1}{2}$" long. All billets were subsequently machined to a diameter of 0.610" prior to hot working.

B. Hot Working

The enriched uranium billets were hot worked separately, in keeping with the accepted practice of limiting the mass accumulation of fissile material in the presence of a moderating medium. The natural uranium billets, on the other hand, were hot worked simultaneously. Each billet was reduced to a diameter of 0.380" by rolling (hand-round roll pass design), then swaged to the final diameter of 0.125"-0.126". The total cumulative percent reduction in area was approximately 95.5%: 61.3% and 34.2% by rolling and swaging, respectively. Both operations were accomplished at 300°C using a commercial heat-treating oil (Mel-Temp #7) as the heating medium. A 30-minute preheat was allowed the individual billets prior to the first rolling pass (0.564" diameter pass). A similar preheat period was allowed after each annealing cycle for rod diameters above 0.250"; this was subsequently reduced to 15 minutes for rod diameters below 0.250". The three-minute reheat period between successive reduction passes was maintained throughout both hot working operations.

The schedule of hot working and annealing procedures applied to the fabrication of the uranium cores is given in Table I.

To avoid the internal "star" cracking that is often observed in heavily worked uranium (particularly in small diameter material heavily cold worked by swaging) each core was given a one-hour anneal at 575°C after each cumulative percent reduction in area of 40 to 45%. A total of six such anneals were required to produce a 0.125"-0.126" diameter x 12 ft long core from the original 0.610" diameter x $6\frac{1}{2}$" long machined billet. These anneals were introduced after successive reductions of 38.0%, 44.7%, 41.0%, 40.7%, 40.0% and 42.8%, as indicated in Table I. In all instances the first and second anneals were carried out in a vacuum annealing furnace having an 18" long heating zone and capable of maintaining a 10^{-5} mm Hg vacuum. All subsequent anneals had to be performed in a 6-ft long horizontal tube furnace with a 48" long heating zone. In the latter case, the

vacuum chamber was a thin wall, 5/8" O.D. x 20 ft long piece of stainless steel tubing closed at one end and lined with 0.010" thick molybdenum sheet. A roughing pump vacuum of 25 to 50 microns was easily maintained during the annealing cycle.

The small diameter, stainless steel tube proved satisfactory from the standpoint of promoting rapid and uniform heating of the uranium cores within, but it also placed a restriction on the number of such cores that could be annealed at one time. Because of this restriction the third and fourth anneals were necessarily performed on individual cores (diameters >0.175"), whereas the last two anneals were performed on core pairs (diameters <0.175").

It was established that approximately 38" of the 48" long heating zone of the tube furnace was uniform in temperature. On the basis of this finding, the uranium cores were annealed in successive 38" long segments, the heating time per segment being one hour at 575°C. With this annealing setup, the time per cycle increased from one hour to four hours as the core length increased from 32" to approximately 12 ft. In retrospect, there is little doubt that a vacuum furnace with a 14 to 16-ft long uniform heating zone would have been preferred, particularly from the standpoint of minimizing the duration of successive annealing cycles.

C. Preparation of the Core for Jacketing

Both ends of the bare core were drilled and tapped (No. 53 drill) to receive the threaded end of a 0.124" diameter x 1/2" long metal plug. After degreasing in liquid carbon tetrachloride followed by an alcohol rinse, the ends of the core were chemically etched in a 50% (by volume) nitric acid solution to remove the surface oxide along a 3" length. A 0.003" thick layer of silver was electroplated over this area to provide a low-resistance electrical path into the uranium core. The end plugs of Type 304 stainless steel or nickel were used to effect a closure with the jacket material by welding or brazing. In the individual helices the end plugs were machined from the same material as that used in the outer jacket.

D. Jacketing the Core

Type 304 stainless steel was used to jacket the first natural uranium-containing helix. This was thereafter abandoned in favor of nickel. The stainless steel, in the form of thin-wall tubing (0.168" dia. x 12 ft long; 0.0075" wall), was received in the hard-drawn condition and had to be annealed to permit further working by cold drawing. The annealing cycle, as in the case of the uranium cores, was carried out under vacuum and in successive 38" long segments, but at the higher temperature of 875°C. The heating time per segment was maintained at one hour. The thin-wall nickel tubing (0.156" dia. x 12 ft long; 0.0065" wall) was used as ordered from the vendor, in a half-soft condition.

Each uranium core was slipped into its jacket with the aid of a 1/8" dia. x 12 ft long carbon steel rod, threaded at one end to match the drilled and tapped holes in either end of the core. The steel rod was easily passed through the small diameter jacket tubing, where its lead end was grasped and held fast while the jacket tubing was pulled over the uranium core. This method of assembly proved more successful than the initially tried method of forcing the core into the jacket tubing. The jacket material was cold-drawn over the uranium core in a conventional drawing operation performed on an "Aetna-Standard" draw-bench (Aetna-Standard Engineering Company, Youngstown, Ohio). This machine has a link-chain actuated carriage and is capable of exerting a pulling force of 15,000 lb. A summary of the drawing operation with reference to the die sizes used is given in Table II. The drawing rate (carriage speed) was kept constant at approximately 20 linear feet per minute.

Three draw passes were used on the stainless steel jacketed rod because of the larger initial jacket diameter and wall thickness. After the second draw pass the measured jacket diameter was 0.139" as indicated in Table II. The jacket thickness was estimated as 0.007" by measuring a dejacketed core section of an accompanying test specimen. The third draw pass succeeded in reducing the core cross section by 12.5% and the jacket thickness by 0.0005". In passing to the nickel jacket one less draw pass was required to obtain the desired core diameter and jacket thickness. The measured diameters of the nickel-jacketed rods corresponded exactly to the final draw-die size (0.138").

A vacuum anneal for one hour at 575°C was given each of the jacketed rods after the final drawing pass. This anneal was carried out in 38" long segments as was the case with the bare uranium cores.

Prior to each draw-pass the lead end of the jacketed assembly was swaged to a diameter slightly less than the draw-die size through which it would be pulled. The draw die was slipped over this end of the jacketed rod before being seated in the die block for drawing. The lead end of the jacketed rod was made to extend from $2\frac{1}{2}$" to 3" beyond the die block to permit gripping by the carriage jaws. This series of steps was repeated for each draw pass after the jacketed rod was turned end-for-end to make a lead end of the former trailing end. It is felt that this reversal of drawing direction served to minimize the amount of cold work suffered by any one end through swaging and, in general, promoted ductility in both the core and jacket materials.

A special device was made with which to grip the lead end of the jacketed rod during the drawing operation without puncturing or otherwise damaging the thin jacket. This device employed the gripping principle of the split lathe collet, using the wedging action of locking tapered surfaces as the closing or gripping force. The general nature of this device and its

application are illustrated schematically in Figure 1. The split collet portion (inner cylinder), drilled slightly smaller than the diameter of the rod to be held, was slipped over the rod and then forced into the larger outer sleeve. By virtue of the matching tapered surfaces the inner cylinder was caused to close tightly around the rod. The carriage jaws were made to grip the outer sleeve during the drawing operation, as indicated in Figure 1. Upon completion of each drawing pass the grip of the collet was broken by forcing the larger outer cylinder off the tapered surface of the collet.

E. Coiling

This operation proved to be the most difficult in the entire fabrication. Any nonuniformities in physical properties of the jacket or core materials not previously detected manifested themselves in the coiling operation, causing rupture or complete fracture in the jacket or core or both. A general view of the coiling setup is shown in Figure 2; a close-up view of the jacketed rod feeding into the coiler is shown in Figure 3. The coiling form consisted of a smooth, 0.997" diameter carbon steel mandrel; the actual coiling was done by a contoured wheel as shown in Figure 3.

At the start of each coiling operation the lead end of the jacketed rod was placed at the approximate center of the horizontal tube furnace and allowed to heat for 20 minutes. The furnace temperature at this point was 450°C, and the temperature in the furnace extension approximately 250°C. The furnace winding and the extension winding were connected in series and controlled by the same variable resistor or Variac. During this initial preheat period the steel mandrel was likewise heated to 250°C with an oxyacetylene torch. The mandrel temperature was estimated with a 480°F Tempilstik. At the conclusion of the preheat period, the lead end of the jacketed rod was fastened to the mandrel by means of a metal clamp (see Figure 3). The contoured wheel was placed over the rod and forced downward until its 1/8" thick lip contacted the surface of the mandrel. The uniform pull of the mandrel being rotated in a lathe (16" Monarch EE) constituted the coiling force. A coiling speed of 12" per minute was used to form the helices.

The application of a lubricant at the point where the jacketed rod passes beneath the contoured wheel was found to be a necessary condition for successful coiling. In the absence of a lubricant the thin jacket material would appear to suffer severe cold work in localized areas and ultimately rupture sometime during the coiling operation. "Molykote" (molybdenum disulfide), a lubricant used frequently in hot extrusion operations, was used in this case.

In selecting the 0.997" diameter mandrel and the contoured wheel shown in Figure 3, it was intended that an 1/8" spacing between turns would be obtained during coiling; the natural springback of the helix would

yield the desired 1" inside diameter. It was found, however, that the spring-back along a given helix and between different helices was not uniform. Likewise, the spacing between turns was reduced to 1/16" by the requestor after the coiling apparatus had been made. Therefore, the desired helix dimensions were obtained by an alternate method, with the aid of a grooved graphite mandrel having the proper groove spacing and root diameter. The coiled helix was "screwed" onto this graphite mandrel and a graphite sleeve was slipped over the assembly to uniformly depress the turns of the helix into the grooves of the mandrel. The entire assembly was vacuum annealed for one hour at 575°C. This technique yielded a uniform helix diameter and spacing between turns, 1" I.D. and 1/16", respectively, irrespective of any differences in the fabricating history.

F. End Closures

Two types of end closures were used, as illustrated in Figure 4. The Type I closure was originally intended for all of the helices and was retained in those helical units that were successfully coiled without fractures. On the other hand, the Type II closure was designed for those helical units in which the original closure was lost due to a rupture occurring at the beginning or end of the coiling operation. In the latter case, a 3/8" long section of the jacket material was stripped off to expose the uranium core. The oxide layer was removed from the surface and face of the exposed core and a conducting layer of 0.005" thick silver foil placed between the uranium core and the electrical contact. The two types of closures were equally effective in their dual purpose of enclosing the core and providing a low resistance path for current flow into the core.

ACCEPTANCE TESTING OF COMPLETED HELICES

Three of the four completed Doppler helices are pictured in Figures 5, 6 and 7. The first natural uranium-containing helix to be completed was transmitted to the requestor immediately upon completion. Data relating to the physical and dimensional properties of the completed helices are summarized in Table III; the chemical purity of the enriched uranium cores in units 3 and 4 is given in Table IV.

All four units were tested for closure integrity and the absence of "hot" spots before being approved for use in the Doppler Experiments. The acceptance test consisted of approximately 80 cycles between room temperature and 250°C, using the simulated heating and cooling technique proposed for the actual experiments. Air samples taken inside the ventilated hood housing the acceptance-test setup served to confirm the integrity of the end closures. The absence of hot spots was verified by visual means.

Acceptance of the helices for the proposed experiments is in itself considered to be an attestation of the adequacy of their conformity to the pre-set specifications. The degree of agreement with dimensional specifications is immediately obvious from Table III. Conformity of the core material to the "isotropic expansion" requirement is less obvious, since this property is, at best, a difficult one to measure. In this instance the general agreement of the experimental results with those predicted by purely theoretical considerations, within the limits of experimental error, is considered to be an indication of reasonable conformity in this respect.

Figure 8 is a photomicrograph showing the grain structure of the uranium core after coiling. This is a longitudinal section taken in the vicinity of a complete fracture which occurred on coiling. The grain coarsening observed in the center of the core is believed to be the result of nonuniform working during fabrication, occasioned by the rapid cooling of the small diameter rod in traveling from the oil bath to the swager. There is no doubt that this condition exerted an adverse effect upon the ductility of the uranium core.

REMARKS

The geometry of the helix presents some interesting possibilities when viewed in terms of a fuel element configuration for a self-regulating nuclear machine. It is possible that self-regulation could be obtained by a decrease in effective fuel density occasioned by the free expansion of the helical element as a result of neutron heating. The regulating effect should be similar to that presently obtained in the EBWR resulting from a change in density of the moderator.

The helices described herein are basically unsuited for such an application because of the proximity of the jacket material to the core and the relatively low-temperature alloying tendencies which iron and nickel exhibit toward uranium. A zirconium or Zircaloy-clad helical fuel element would appear to be acceptable if techniques were developed to form such an element. The clad core could be produced by a coextrusion technique similar to that being developed at present for the production of the Zircaloy-clad Mark-III fuel loading for EBR-I.

ACKNOWLEDGEMENT

The author wishes to express his appreciation to W. H. Morris and R. R. Langel of the Metallurgy Division for their assistance in fabricating the cores, and to J. W. Hollister and B. J. Mikolajeski of the Central Shops for their assistance in the jacket drawing and coiling operations.

REFERENCE

1. Kato, W. Y. and Butler, D. K., "Measurement of the Doppler Temperature Effect in an EBR-I Type Assembly," to be published.

TABLE I

Schedule of the Hot-Working and Annealing Procedures Used in Fabricating the Uranium Cores

Hot Rolling (Round Roll-Passes)

Pass No.	Dia. (inch)	Calc. Core Length (inch)	Cross-Section Area (Sq. inch)	% Red. in Area per Pass	Cumulative % Red. in Area	Cumulative % Red. in Area between Anneals				
10	0.610	6.00	0.292	-						
11	0.564	7.02	0.249	14.5	14.5					
12	0.520	8.20	0.212	14.8	27.4					
13	0.480	9.70	0.181	14.8	38.0					
Annealed 1 Hour at 575°C										
14	0.443	11.40	0.154	14.8	47.3	14.8				
15	0.409	13.40	0.131	14.7	55.1	27.6				
16	0.390	14.70	0.120	10.0	58.9	33.7				
17	0.380	15.50	0.113	5.1	61.3	37.6				
Hot Swaging										
10	0.382		0.115	-	-	-				
11	0.358	17.40	0.100	13.0	65.8	44.7				
Annealed 1 Hour at 575°C										
12	0.336	19.70	0.089	11.0	69.5	-	11.0			
13	0.315	23.00	0.078	12.3	73.3	-	22.0			
14	0.295	25.60	0.068	12.8	76.7	-	32.0			
15	0.274	29.80	0.059	13.2	79.8	-	41.0			
Annealed 1 Hour at 575°C										
16	0.259	33.30	0.053	10.2	81.8	-	-	10.2		
17	0.244	37.80	0.047	11.3	83.9			20.3		
18	0.225	43.70	0.040	14.9	86.3			32.2		
19	0.212	49.50	0.035	12.5	88.0			40.7		
Annealed 1 Hour at 575°C										
20	0.199	55.80	0.031	11.4	89.4				11.4	
21	0.186	63.70	0.027	12.9	90.7				22.8	
22	0.174	72.00	0.024	11.1	91.8				31.4	
23	0.164	82.60	0.021	12.5	92.8				40.0	
Annealed 1 Hour at 575°C										
24	0.153	97.00	0.018	14.3	93.8					14.3
25	0.144	106.20	0.016	11.1	94.5					23.8
26	0.136	124.00	0.014	12.5	95.2					33.3
27	0.125	140.00	0.012	14.3	95.5					42.8
Final Anneal 1 Hour at 575°C										

TABLE II

A Summary of Draw Die Sizes Used in the Jacketing Operation

Jacket Material	Type 304 S.S.		Nickel	
Initial Jacket O.D.	0.168"		0.156"	
Lead End Swaged to:		0.154"		
		0.144"		0.144"
First Draw-Die Pass	0.145		0.145	
Lead End Swaged to:		0.136"		0.136"
Second Draw-Die Pass	0.138" *(0.139")		0.138" *(0.138")	
Lead End Swaged to:		0.128"		None
Third Draw-Die Pass	0.131" *(0.132")		None	

*Measured diameters.

TABLE III

A Summary of Some Properties of Four Jacketed Uranium Doppler Helices

Unit No.	Casting No.	Gross Wt. (grams)	No. of Turns	Jacketed Dia. (inch)	Uranium Core		Jacket		Remarks
					Diameter (inch)	Weight (grams)	Material	Thickness (inch)	
1	SNY-28	479	36	0.132	0.118-0.119	434.94 (±2%)	304 S.S.	0.0065	Core - U^{238} Type-2 End Closures
2	SNY-28	425.45	29	0.138	0.125-0.126	387.12 (±2%)	Nickel	0.006	Core - U^{238} One each of Type-1 & Type-2 End Closures
3	Y16F-178	561.07	37	0.138	0.126-0.127	511.13 (±1%)	Nickel	0.0055	Core - U^{235} One each of Type-1 & Type-2 End Closures
4	Y16F-180	600.67	40	0.138	0.125-0.126	542.79 (±1%)	Nickel	0.006	Core - U^{235} Type-1 End Closures

TABLE IV

Spectrochemical Analysis Results Obtained From Samples of the Enriched Uranium Cores of Helical Units 3 and 4

Casting No.	Ag	Al	As	B	Be	Bi	Ca	Co	Cr	Cu	Fe	K	Li	Mg
Y16F-178	L1	20	L10	1	L0.5	L1	L20	L5	3	3	150	L100	L1	20
Y16F-180	L1	10	L10	1	L0.5	L1	L20	L5	3	3	70	L100	L1	7
	Mn	Mo	Na	Ni	P	Pb	Sb	Si	Sn	Ti	Zn			
Y16F-178	7	30	2	15	L50	L1	L1	50	L5	L50	L50			
Y16F-180	5	30	L2	15	L50	L1	L1	50	L5	L50	L50			

Note: Similar results would be expected for helical Units 1 and 2 containing normal uranium cores.

FIGURE 1. Illustration of the nature and application of the rod gripping device.

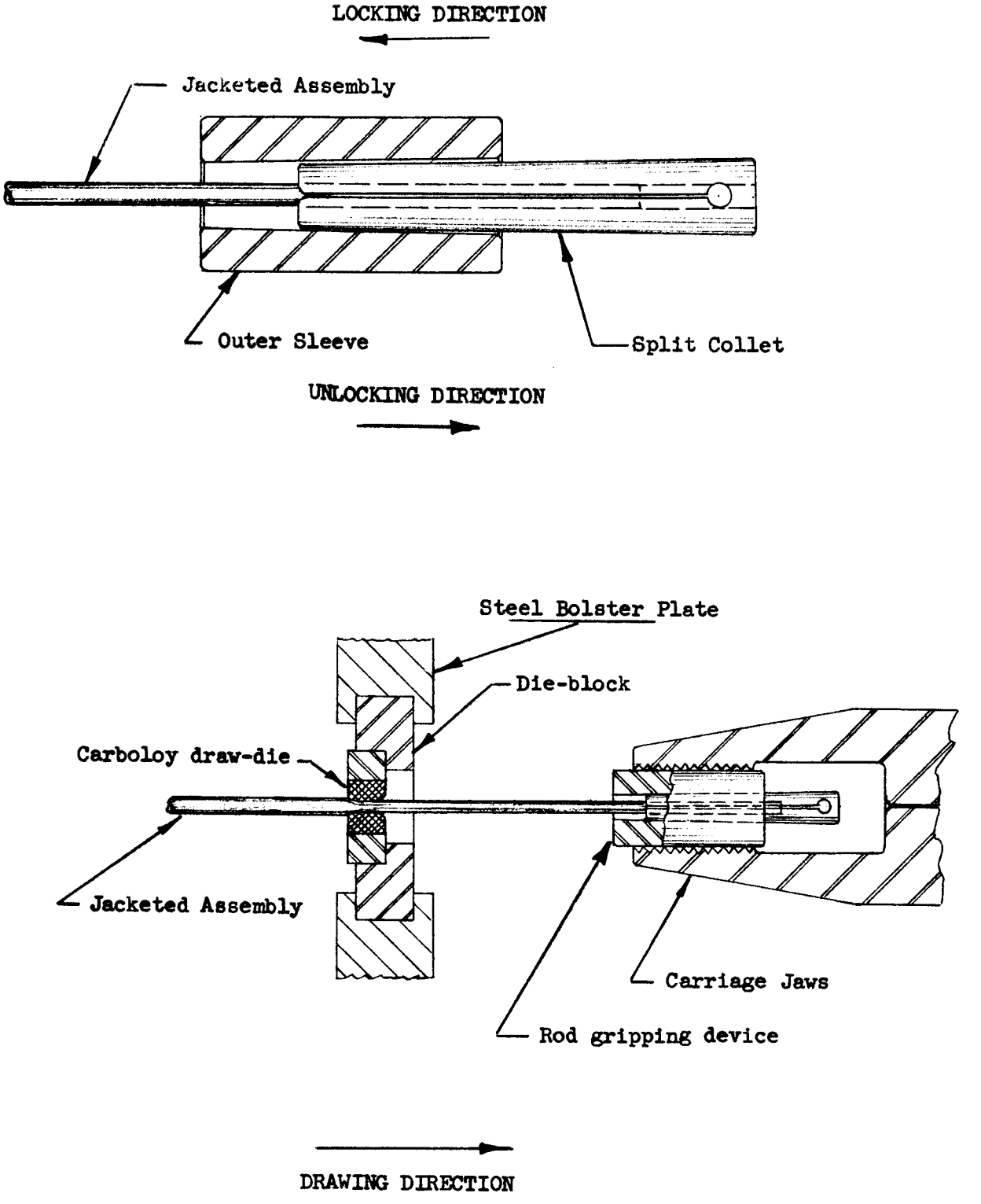
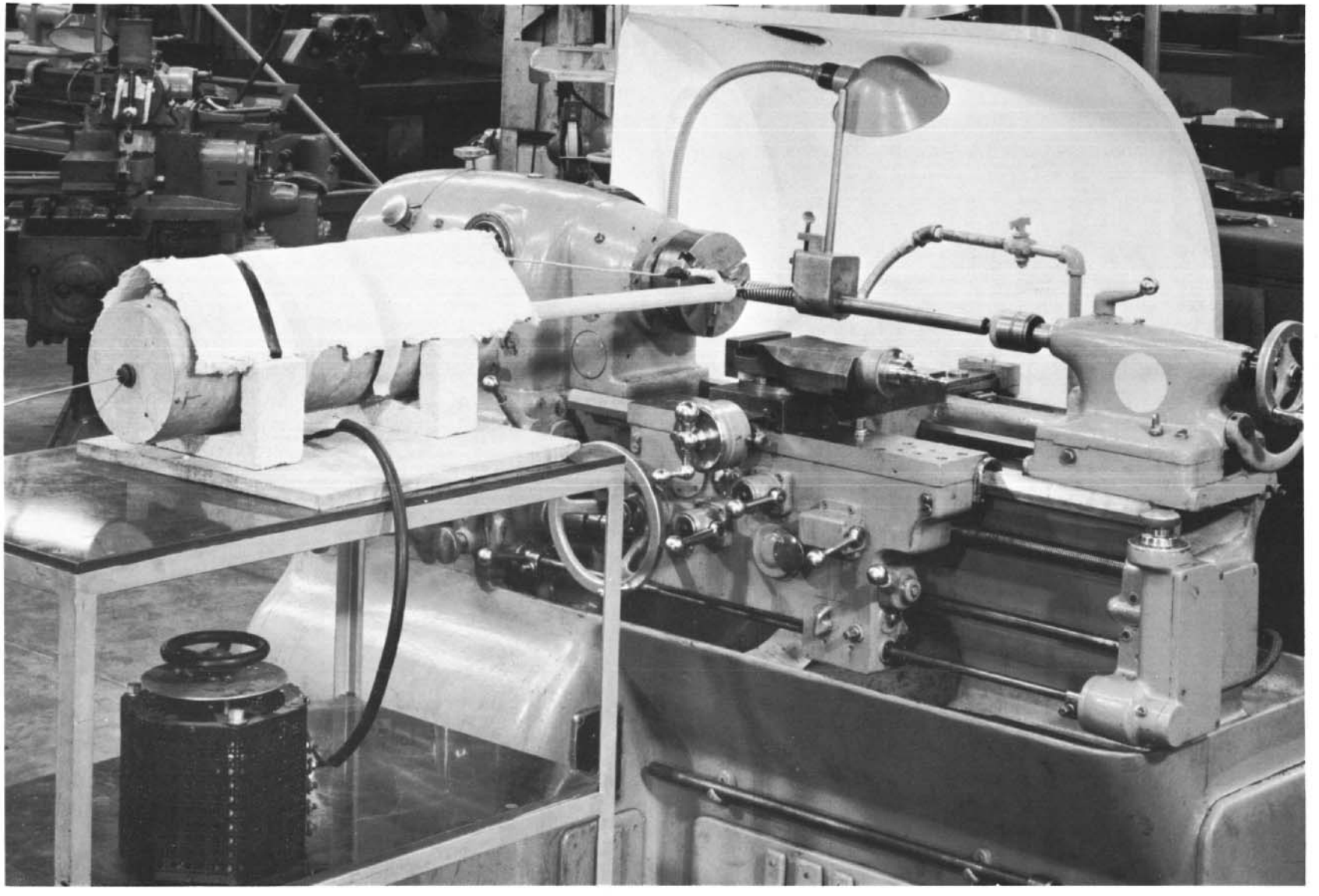


FIGURE 2. A General View of the Helix Coiling Setup.



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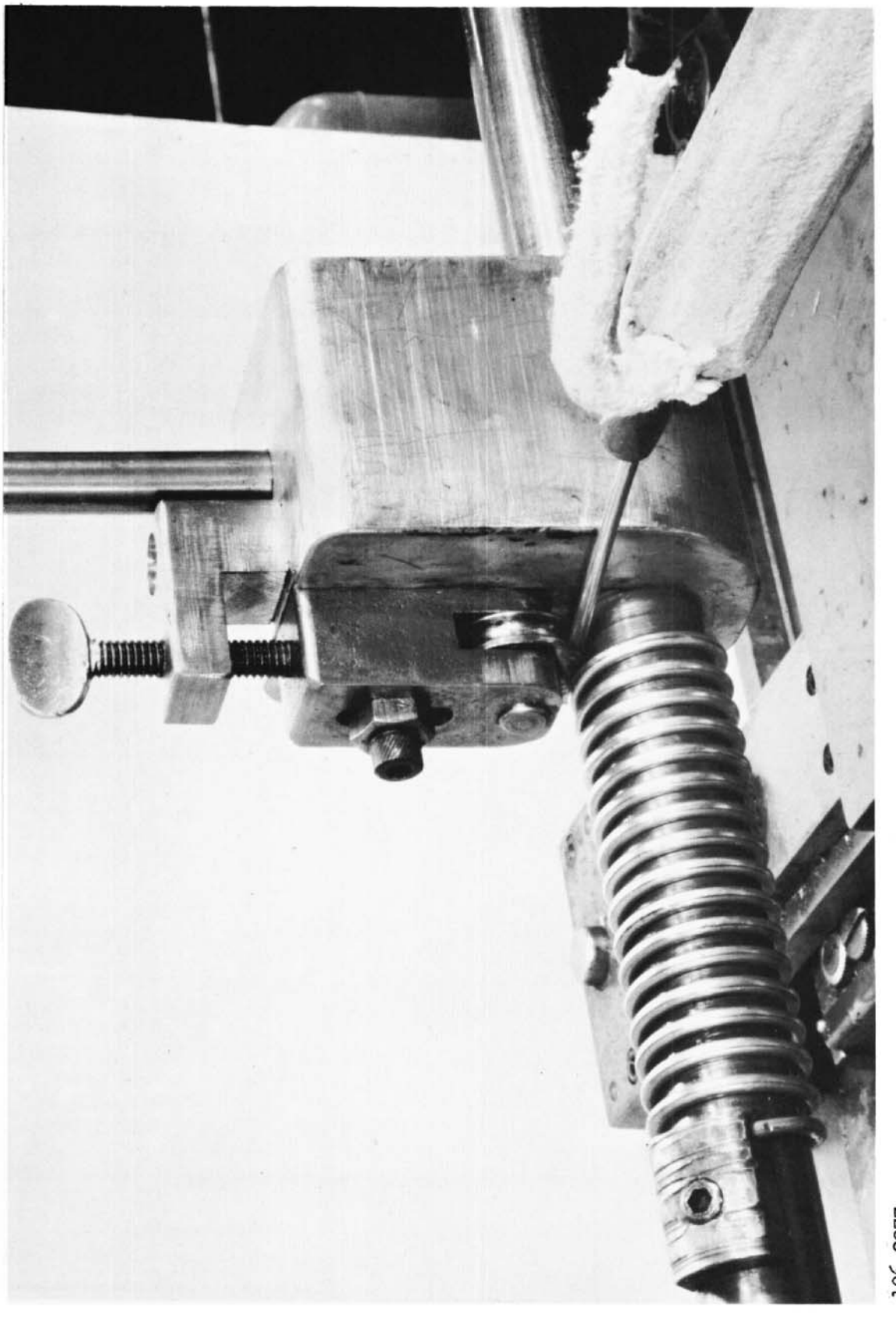

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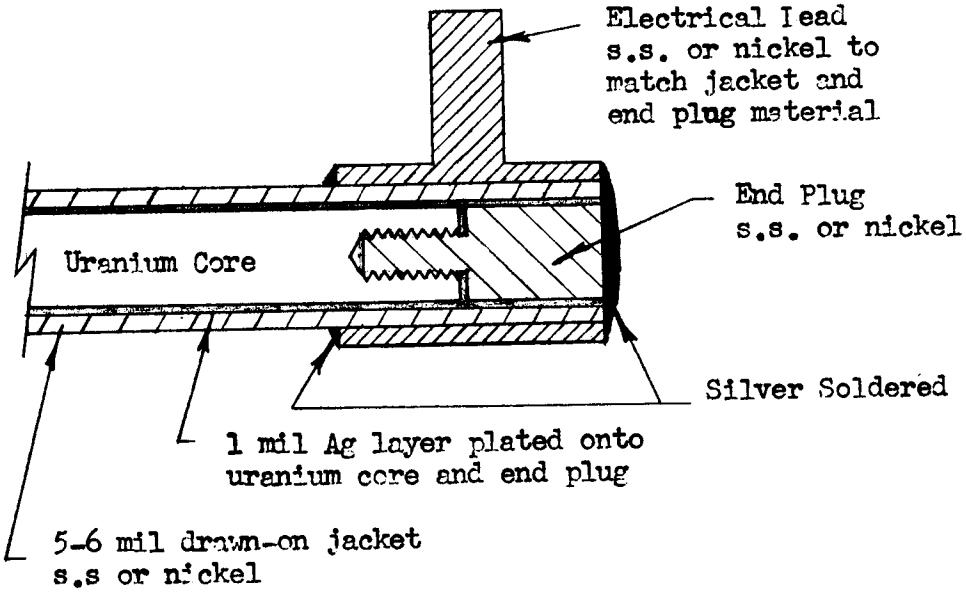
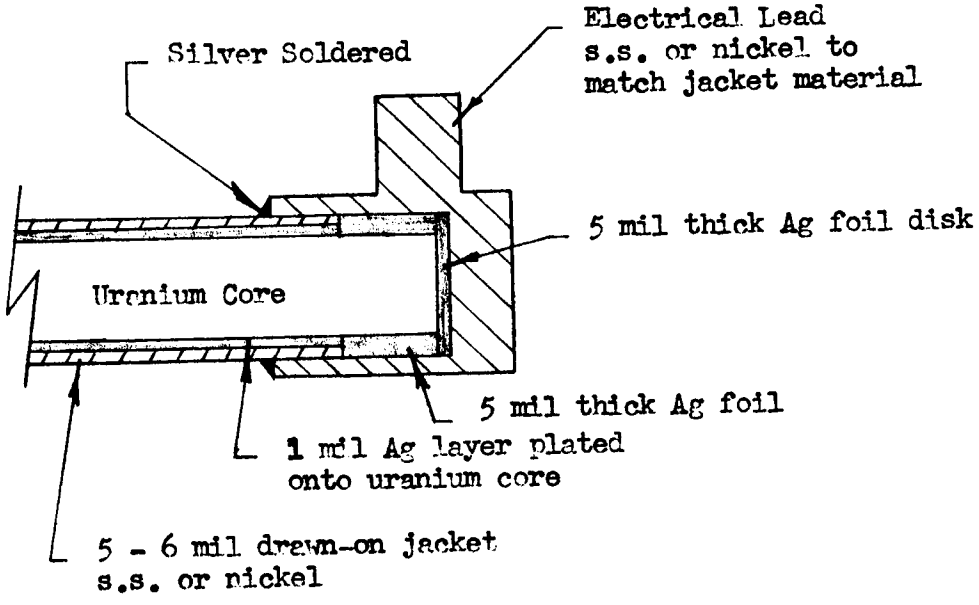
FIGURE 3. Close-up View of the Coiling Operations.

Figure 4 END CLOSURES USED ON THE JACKETED URANIUM DOPPLER HELICES



Type I End Closure



Type II End Closure

FIGURE 5. Natural Uranium-Containing Helix
(Unit 2)

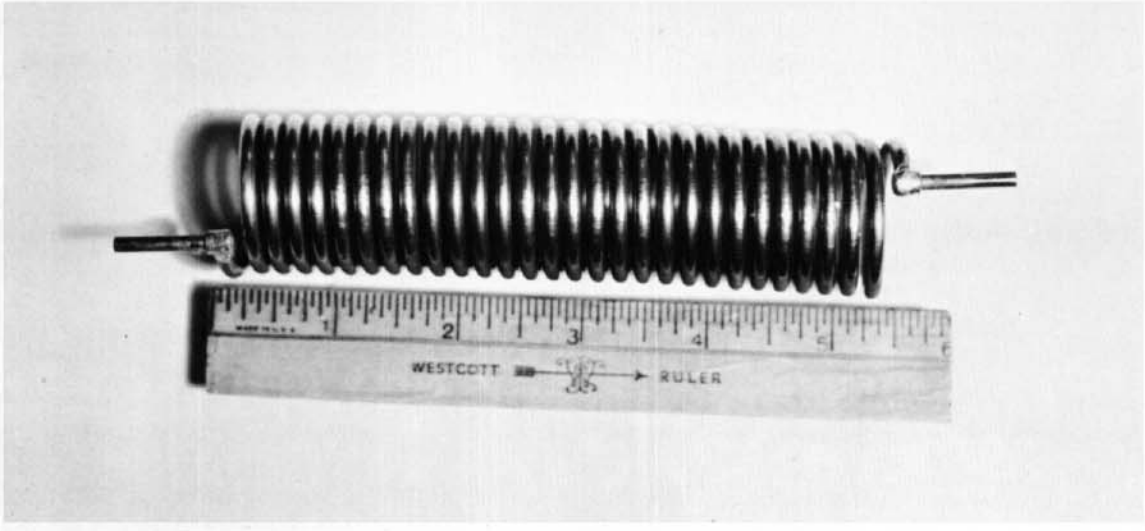


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FIGURE 6. Enriched Uranium-Containing Helix
(Unit 3)

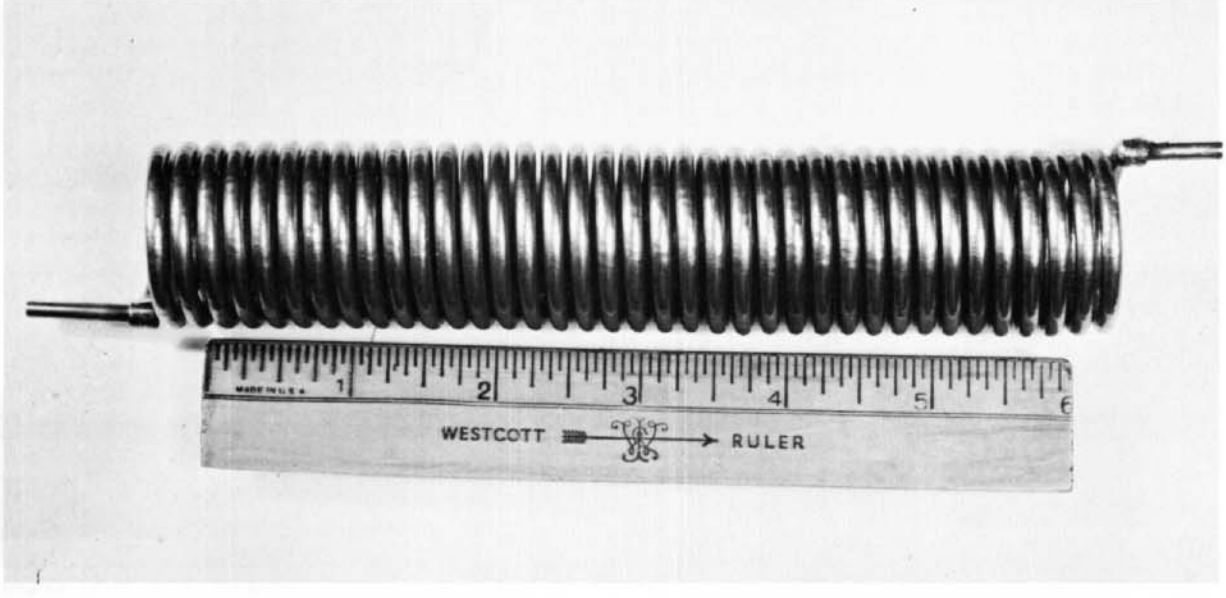

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FIGURE 7. Enriched Uranium-Containing Helix. (Unit 4)

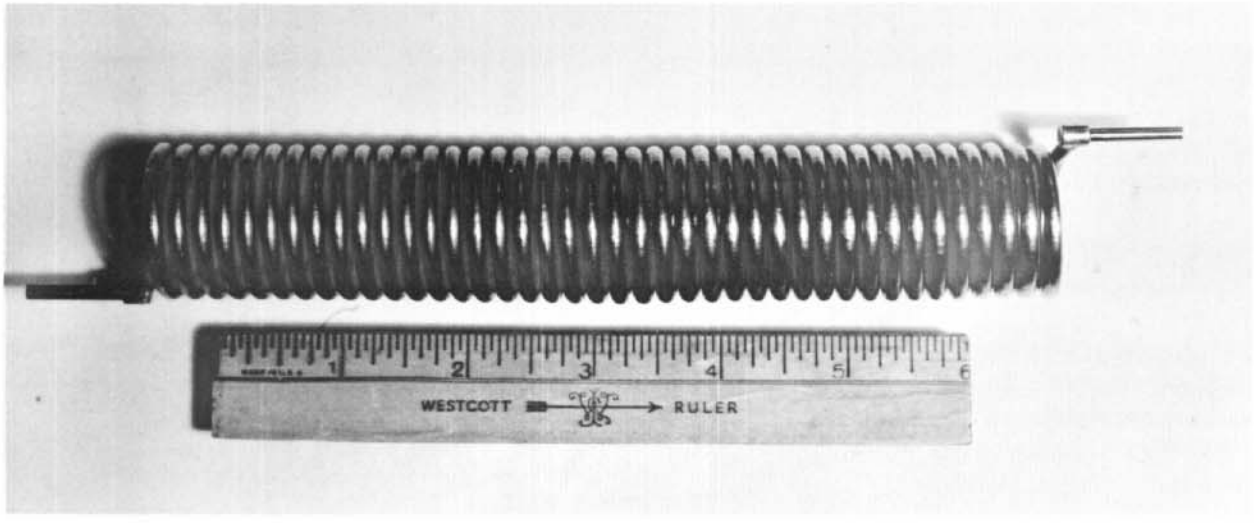

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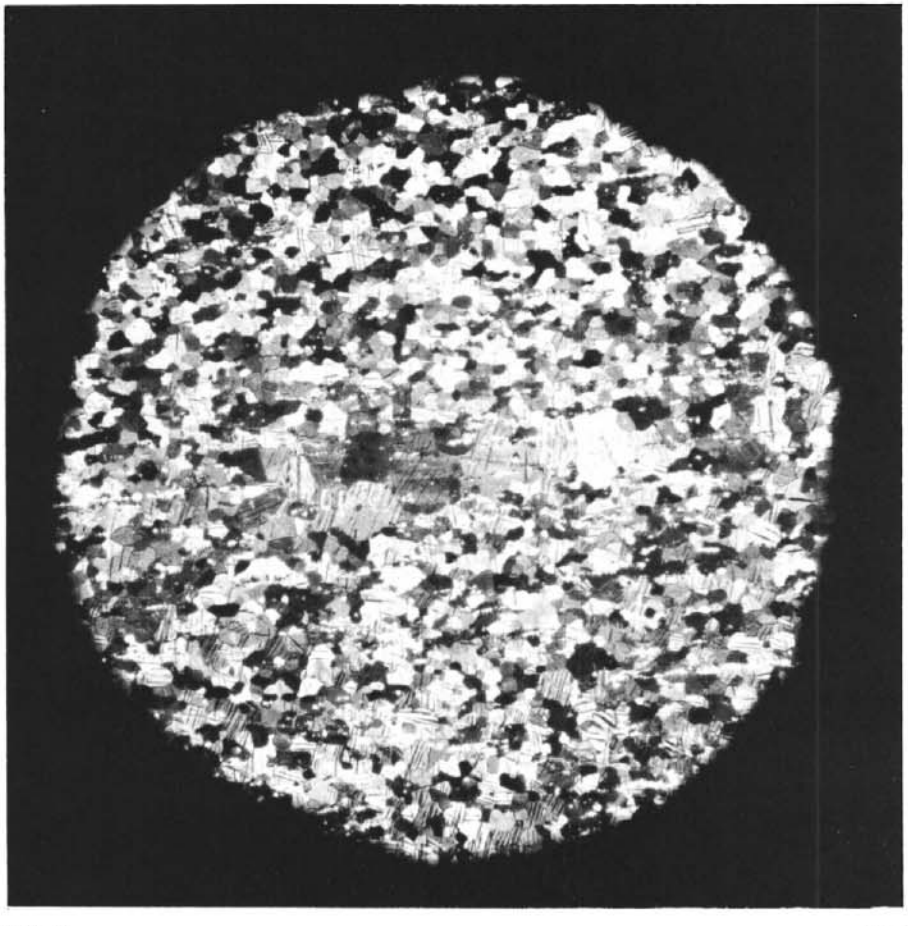
FIGURE 8. Longitudinal Section of Uranium Core.



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ADDENDUM TO
ANL-5690

THE FABRICATION OF CERTAIN JACKETED URANIUM HELICES

By

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Please add to the ACKNOWLEDGEMENT on page 11 the following:

> The coiling device was conceived and built through the joint efforts of R. J. Dunworth of the Metallurgy Division and A. P. Hryn of Central Shops, in connection with a similar helix fabrication containing a plutonium metal core.

Alvin Glassner
Information Division

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