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Argonne National Laboratory

THE MANUFACTURE OF ENRICHED URANIUM FUEL SLUGS FOR THE EXPERIMENTAL BREEDER REACTOR

by

Arthur B. Shuck

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Metallurgy and Ceramics
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Arthur B. Shuck

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THE MANUFACTURE OF ENRICHED URANIUM FUEL SLUGS FOR THE EXPERIMENTAL BREEDER REACTOR

by

Arthur B. Shuck

ABSTRACT

This report describes the specifications, materials and the sequence of operations used to found and fabricate the first charge of enriched uranium fuel in the Experimental Breeder Reactor.

The work was governed by the following principles:

a. That the fuel be of correct composition, dimension and metallurgical condition for use in the reactor.

b. That a maximum yield of finished fuel slugs from the quantity of uranium available for the program be achieved.

c. That the residues be in a form which can be recovered by chemical or other means.

d. That a detailed record be kept in such form that a complete history of each fuel slug be available.

Deviations from the standard process are discussed. Quantitative data is presented to show the over-all yield of fuel from the process and the quantities of material in the residues. The method of ignition of turnings is described together with quantitative data on the operation.

A complete and detailed log of the founding and fabricating of each batch of material processes is given in Appendix A.[3] Complete data on the loading of the fuel rods is given in Appendix B.[4]

INTRODUCTION

The purpose of this report is (1) to provide a metallurgical history of the first fuel charge for the Experimental Breeder Reactor, (2) to describe the assembly of the fuel sections of the fuel rods and (3) to present quantitative data on the utilization of the U-235-enriched uranium supplied for the reactor.

This charge of fuel, in the form of cylindrical slugs, was fabricated from unalloyed 93-94 w/o U-235-enriched uranium which was supplied to ANL as Y-12 reduction buttons. Delete The limited quantity available and the great value of the enriched uranium made it necessary to eliminate every possible source of waste of the material and to establish a rigorous accounting system for each step of the process. Unaccountable losses and uranium in unrecoverable residues were to be essentially zero. It was required that (1) the yield of fuel slugs be as high as possible and (2) that the residues be in a form allowing chemical recovery.

Further requirements were made that the fuel slugs be in the best known metallurgical condition to resist the in-pile radiation effects; that each slug supplied be of known composition and have a known metallurgical history, from the melting of the raw material to the assembly of the fuel rods, for future reference in disassembly and chemical processing of the rods.

The methods and equipment for processing the enriched uranium were first developed using normal uranium. The normal uranium slugs were tested metallurgically and were thermal cycled to determine their dimensional stability and their suitability for use in the reactor. The processes developed and the results of the tests have been described in detail in ANL-4617.[1] The fabrication processes will therefore be described only briefly in this report.

SPECIFICATIONS

The following analytical, dimensional and metallurgical specifications were set for the EBR fuel. Any deviation from these specifications was subject to approval by the EBR project engineer.

Compositional Limits:

Enrichment

$$93.0 - 94.0 \text{ w/o } U^{235}$$

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Maximum Impurities (ppm)

Al	5.0	Li	1.0	V	200.0
B	0.5	Mg	100.0	Cr	200.0
Be	0.1	Na	3.0	Co	200.0
Ca	100.0	Si	100.0	Ni	200.0
Fe	200.0	Mn	200.0	Cu	10.0

Dimensional Tolerances:

Three sizes of slugs were made to the following dimensions:

	Diameter	Length
(1)	0.363"-0.366"	1.871"-1.874"
(2)	0.383"-0.386"	2.514"-2.517"
(3)	0.383"-0.386"	1.665"-1.668"

The method of separating the slugs from the fabricated rod was selected to produce a minimum of cuttings. Occasionally a slug was broken shorter than the length tolerance. Compensation for a short length slug by a long slug used in the same fuel rod was allowed.

Metallurgical Specifications:

The metallurgical requirements to produce dimensionally stable fuel were (a) that the grain structure be fine, and (b) that the grains be of random orientation. (2) Moderately fine grained, randomly oriented metal was formed by quenching from the beta phase (725°C). Randomness was tested indirectly by a dilatometer test, which will be explained later. An additional requirement was that the slugs be without cracks or internal imperfections which might cause disintegration in use or might reduce the density of the fuel slugs.

RAW MATERIAL

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The feed material for the fabrication of the fuel slugs was received from Y-12 in the form of reduction buttons. In general, these were free of slag and had clean unoxidized surfaces. One button contained a considerable quantity of entrained slag and some unreduced fluoride. This button was crumbly and had a strong, sharp odor. It was returned for a new button. The first 42 buttons weighed between 1092 and 1195 grams each and, with a portion of a 43rd button received to complete the initial order, had a total weight of 50,188.94 grams. Seven additional buttons and a fragment were received on a supplemental order which weighed between 2167 and 2367 grams each. The weight of the fragment was 362 grams. The total weight received on the supplemental order was 16,174.12 grams giving a total of 66,363,06 grams of material entered into process before sampling.

This material was processed in approximately two-kilogram batches, using two of the smaller buttons, one of the larger buttons, or one of the smaller buttons and approximately one kilogram of return scrap. Oak Ridge analytical data was used in the computation of the charge analyses. An attempt was made to average out anomalies in button composition by combining buttons of high purity with those of lower purity. Several buttons out of specification on iron and silicon were used successfully by this method. The method was not successful with buttons issued as ANL Batch Numbers 2-310-8 and 2-310-9 and the slugs fabricated from these batches were exchanged for material of higher purity.

Table I shows a comparison of isotopic compositions computed from Y-12 analyses and ANL analyses of the castings as supplied by the Special Materials Department Analytical Group.

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Table I

ANALYSIS OF CASTINGS COMPUTED FROM Y-12 ANALYSES
COMPARED WITH ANL ANALYSES

Casting No.	SM Batch No.	% U-235 Y-12	% U-235 ANL	% U-238 Y-12	% U-238 ANL	% U-234 Y-12	% U-234 ANL
16F 1	2-280	93.84	93.94	5.21	5.12	.95	.94
2	2-285	93.32	93.40	5.59	5.55	1.07	1.05
3	2-287	93.38	93.44	5.56	5.52	1.06	1.05
4	2-290	93.29	93.38	5.62	5.56	1.07	1.06
5	2-291	93.55	93.62	5.46	5.40	.99	.98
6	2-298	93.30	93.38	5.62	5.56	1.05	1.06
7	2-299	93.40	93.45	5.56	5.55	1.03	1.00
8	2-300	93.65	93.73	5.34	5.29	1.00	.98
9	2-301	93.87	93.90	5.18	5.17	.94	.93
10	2-302	93.66	93.68	5.33	5.33	1.01	.99
11	2-313	93.29	93.29	5.55	5.59	1.13	1.12
12	2-314	93.40	93.40	5.46	5.53	1.07	1.07
13	2-315	93.34	93.28	5.56	5.62	1.07	1.10
14	2-318	93.19	93.26	5.66	5.58	1.17	1.16
15	2-317	93.44	93.44	5.47	5.50	1.06	1.06
16	2-320	93.39	93.45	5.42	5.41	1.14	1.14
17	2-326	93.21	93.24	5.58	5.55	1.19	1.21
18	2-328	93.42	93.38	5.49	5.54	1.05	1.08
19	2-329	93.13	93.39	5.65	5.51	1.20	1.10
20	2-331	93.29	93.22	5.58	5.59	1.13	1.19
21	2-332	93.28	93.22	5.52	5.65	1.17	1.13
22	2-334	93.29	93.40	5.53	5.46	1.15	1.14
23	2-336	93.25	93.35	5.58	5.51	1.15	1.14
24	2-340	93.24	93.18	5.53	5.67	1.14	1.15
25	2-341	93.45	93.45	5.42	5.47	1.10	1.10
35	2-395-1	93.24	93.23	5.67	5.67	1.09	1.10
36	2-395-2	93.23	93.24	5.68	5.67	1.09	1.09
37	2-400-1	93.21	93.22	5.68	5.67	1.11	1.10
38	2-400-2	93.13	93.19	5.86	5.77	1.04	1.04
39	2-400-3	93.23	93.21	5.73	5.76	1.04	1.03
40	2-400-4	93.19	93.20	5.75	5.76	1.06	1.04
41	2-403	93.22	93.27	5.71	5.67	1.07	1.06
42	2-419	93.27	93.23	5.70	5.71	1.03	1.06
Numerical Average		93.33	93.37	5.55	5.54	1.08	1.07

SEQUENCE OF OPERATIONS

The normal manufacturing sequence for the fuel slugs is shown in a flow chart, Figure 1.

Preparation of the charge:

Equipment used

a. Five kilogram capacity analytic balance
b. Two-hundred gram capacity analytic balance
c. Wide mouth Dewar flask
d. Tongs
e. Hooded hydraulic press
f. Rectifier
g. Beakers for electrocleaning and washing
h. Platinum fixture
k. Sample bottles

Materials

Delete

a. Enriched uranium reduction buttons or remelt stock
b. Liquid nitrogen
c. Electropolishing solution
d. Distilled water and acetone

Melting charges were limited to approximately 2400 grams for convenience in handling through the subsequent fabrication operations. The melting charge consisted either of two of the smaller buttons, one of the larger buttons, or return remelt stock plus a small button or a portion of a larger button. The reduction buttons were weighed to the milligram as received. Each button was then chilled in liquid nitrogen to promote a brittle fracture and broken on a ten ton hydraulic press. The work zone of this press was enclosed to prevent loss of the fragments. Clean fragments were selected for isotopic and spectrographic determinations. The hood was then carefully cleaned out and all of the fragments weighed before breaking another button. A broken reduction button is shown in Figure 2.

Duplicate samples were taken for isotopic and spectrochemical analysis. One set of these was transmitted to the analytic laboratories for their work. The remaining samples were held in the vault for reference in case the original sample produced a variation from the analyses shown by Y-12. Originally approximately one gram was taken from each button. Later this was reduced to 0.300 to 0.500 gram.

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The total weight of uranium melted after sampling was 66,337.191 grams. A total weight of 23.608 grams of sample was taken. Unusable residue from the breaking operation amounted to 2.261 grams.

Considerable difficulty was experienced in breaking the two-kilogram buttons. This may account for the larger losses on this operation when the two-kilogram buttons were broken.

The remelt stock consisted of rod ends or scrap slugs from previous batches, plus any loose particles that were recovered from the melting or fabricating operations. Turnings were not remelted. The rod ends or scrap slugs were degreased in commercial solvent, rinsed in acetone and air dried. They were then weighed and the oxide removed by anodically cleaning in a solution consisting of 46 v/o H_2SO_4, 9 v/o glycerine, 45 v/o water. The polished pieces were rinsed through water and acetone, dried and reweighed. This material was of pre-calculated composition. The total quantities of U-234, U-235, U-238 and the principal impurities were computed and the composition figured of the new charge.

Melting and casting:

Equipment used

a. High-vacuum, induction melting furnaces (Drawing CS-1307)
b. Pumping equipment capable of maintaining 10^{-5} mm of Hg.
c. Vacuum gages
d. Tantalum heater
e. Water cooled mold (1-1/4" dia., x 10" deep)
f. Induction heating generator (15 kw, 10,000 cycle)
g. Optical pyrometer
h. Dewar flasks

Materials

a. Previously prepared charge
b. Magnesia crucible, stopper rod, cover and pedestal
c. Liquid nitrogen
d. The usual oils and greases used in high vacuum techniques

The magnesia ceramics, consisting of a type V-2 crucible, stopper rod and cover, were stored in an oven maintained at about 150°C. These were dessicator cooled and weighed to the nearest milligram. The crucibles measured about 3-1/2" in diameter by 9" deep, tapering to the bottom pour hole for drainage. The crucible, with the charge in place, was set upon a specially designed magnesia pedestal which supported the crucible bottom, acted as a funnel between the crucible and the mold and insulated the crucible from the water cooled mold. A stainless steel spider attached to the mold supported the tantalum heater and zirconia insulator. A 5-3/4" diameter by 27" Vycor tube was placed over the above assembly and sealed to the vacuum system by a silicone rubber gasket. A furnace top with a quartz sight window and a water-cooled stopper rod manipulator completed the furnace assembly.

A vacuum of the order of 5×10^{-5} mm of Hg was maintained on this system by a six-inch, fractionating, oil vapor pump backed by a six-inch booster and a two-stage mechanical pump. The furnace was heated by induction power supplied by a 15 kw, 220 v, 10,000 cycle motor-generator.

Temperature was read by means of an optical pyrometer sighted upon the heated metal through sight holes in the crucible cover and cover heater, a quartz window in the furnace top and through a right angle prism on the top of the furnace. A thin film of vacuum grease on the inside of the sight window kept it from becoming coated by an evaporated metal film. The melting furnace is shown in Figure 3.

In operation, the system was pumped down to approximately 10^{-5} mm of Hg pressure. Power was applied slowly to allow the ceramics to heat uniformly. A heating rate of about 700°C per hour prevented crucible breakage between room temperature and 1000°C. Above 1000°C, it was found that the crucibles could be heated more rapidly without breaking. Melting required about 15 minutes at 7 kilowatts input. After melting the metal was superheated to 1365°C in about 15 minutes and the heat poured by lifting the stopper rod. It was found desirable to pour the metal as soon as possible after reaching temperature because there was some erosion of the crucibles and stopper rods at 1365°C.

The furnace was cooled under vacuum, usually overnight. After cooling the furnace was torn down, the castings, ceramics, shot and skull removed and weighed. The weight totals before and after casting showed a difference of about 1-1/2 grams. This was found to be principally due to the reduction and volatilization of magnesium from the crucible and stopper rod. Deposits upon the inside of the furnace were analyzed and found to be magnesium with only traces of uranium.

The castings produced required no further treatment for fabrication. Their surfaces were clean and bright and showed a marked freedom from surface defects. One of the castings produced is shown in Figure 4.

Gamma radiography:

Equipment used

a. 0.42 curie cobalt-60 source
b. Shielded radiographic chamber
c. Paper film holders

Materials

a. No-screen x-ray film

Each casting was gamma radiographed to show any gross porosity. The following exposures gave satisfactory film densities:

Film focal distance, inches	50	36	25
Exposure time, hours	16	8	4

The 50-inch film focal distance produced the best definition, but there was some autoradiographic fogging of the film by the casting. This was largely eliminated by use of a 0.025" lead sheet between the casting and the film holder.

Except for a shrinkage depression in the top of each casting, usually about 3/4" deep, no large cavities were found. Several castings showed evidences of microshrinkage, particularly in 16F24 and 16F25, but this did not seem to affect the finished fuel slugs.

Fabrication:

Equipment used

a. Oil heating tank with controller
b. Rolling mill (8-3/4" x 20" United)
c. Rounding rolls (Drawings C-1024 and D-1024)
d. Rod tongs
e. Micrometers
f. High vacuum annealing furnace

Materials

a. 350°C flash point heating oil
b. Commercial solvent and carbon tetrachloride
c. Wiping cloths

The castings, measuring 1-1/4" in diameter by approximately 5-1/2" long, were heated to 300°C by immersion in the oil bath for ten minutes. The oil bath was normally operated at 305°C to 315°C. After preheating, the rods were rolled from 1-1/4" to 0.66" diameter in nine reductions. Each reduction was made by triple passing through the roll opening, turning the rod 90° each time through, then soaking for one minute in the oil bath before making the next reduction.

The total reduction from the original casting diameter was 72 per cent. The rods were then wiped, cleaned through carbon tetrachloride, commerical solvent and acetone and weighed. The next step was a one-hour anneal at 725°C. A resistance-heated, horizontal, high-vacuum tube furnace was used. Vacuums under 10^{-5} mm of Hg were ordinarily maintained during this operation. After one hour at temperature, the rods were pulled to a water-cooled section of the furnace tube and cooled under vacuum to room temperature. They were then removed from the furnace and weighed.

The 0.66" diameter, beta annealed rods were rolled to 0.010" over finished diameter in seven or eight reductions at 300°C depending upon whether 0.284" or 0.364" rod was required. Table II shows the schedule of reductions.

Table II

ROLLING MILL PASS SCHEDULE FOR EBR FUEL FABRICATION

Pass No.	Nominal Diameter	Sq. In. Sectional Area	% Red. per Pass	Cumulative Per cent Red.	Rod Diameter
1.	1.250	1.227	----	----	1.245
2.	1.152	1.043	14.9	14.9	1.152
3.	1.062	.883	14.9	27.8	1.064
4.	.981	.756	14.7	38.4	.987
5.	.905	.643	14.9	47.4	.905
6.	.836	.549	14.7	55.3	.839
7.	.772	.469	14.7	61.8	.773
8.	.714	.400	14.6	67.4	.714
9.	.660	.342	14.6	72.2	.660
Vacuum anneal at 725°C for one hour					
10.	.610	.292	14.6	14.6	.610
11.	.564	.249	14.5	27.2	.565
12.	.520	.212	14.8	37.9	.520
13.	.480	.181	14.8	44.0	.475
14.	.443	.154	14.8	55.1	.442
15.	.409	.131	14.7	61.6	.406
16.	.390	.120	10.0	64.2	.390
17.	.380	.113	5.1	67.0	.375

The rolled rod, now 60 to 70 inches long, was brought to size and straightened in one operation by swaging through a rotary swaging machine. The finished rods were round to within 0.001" and the surface was very smooth. When fabrication was done properly, no laps occurred. The rod was degreased by washing in trichloroethylene and acetone.

Division of the Rod into Slugs:

Equipment used

a. Hooded EE-10" Monarch lathe
b. 60° sharp threading tool
c. 23/64" collet
d. Steady rest and head stock stand
e. Micrometer carriage stop
f. Dewar flask
g. Hooded hydraulic press
h. Breaking die

Material

a. Liquid nitrogen

The cut-off methods most commonly employed on uranium are the use of abrasive saws, milling saws and single point cut-off tools. The following method was found to be simpler, faster and less wasteful of enriched uranium than the other methods. Annular grooves were cut around the rods to a depth of 0.038" using a carbide-tipped, 60°-sharp, threading tool at intervals about 0.030" greater than the length of the finished slugs. This allowed for contraction of the length during beta treatment and for facing to length. After notching, the rod was immersed in liquid nitrogen and then transferred to the press and slugs were snapped off at the notches. The slugs were dried and weighed. The turnings and chips were carefully collected and weighed and the total weights were compared with the weight after beta annealing to show the weight of uranium in the fabricating residue.

Fracture inspection:

Equipment used

a. Low power binocular microscope

The freshly fractured surfaces of the ends of the slugs were inspected for cracks, center pipes or other internal imperfections. The cylindrical surfaces were also examined for laps or flakes. The rod ends and any reject slugs were set aside as remelt stock.

Beta treating:

Equipment used

a. Lead pot furnace
b. Quenching apparatus
c. Sealable heat treating tubes
d. Vacuum pump
e. Gas regulator

Material

a. Purified argon
b. Distilled water
c. Acetone

The slugs were dimensionally stabilized by heating in argon-filled tubes to 725°C by means of a lead bath. It was found that 15 minutes in the lead bath was sufficient to heat the slugs and for transformation to take place. The slugs were then dumped out of the tubes into flowing water in the quenching apparatus. A closed-cycle quench system was used to save any oxide which formed by reaction between the water and the hot slugs. This contained about five gallons of distilled water to which a half pound of Na_2CO_3 was added to inhibit corrosion of the system. The water was pumped through a 1/2 gallon quench tank at a rate of about 8 gallons per minute.

The slugs were weighed after beta treating.

Alpha anneal:

Equipment used

a. High-vacuum, horizontal-tube annealing furnace
b. Stainless steel boat or fixture

The beta treated slugs were annealed for two hours at 575°C at about 10^{-5} mm of Hg in the same furnace used for beta annealing during fabrication. After annealing the slugs were again weighed.

Heat treating caused considerable dimensional change in the slugs. They contracted in length from 0.015" to 0.018" and increased in diameter about 0.0015 to 0.002". They were also out of round and somewhat warped. The 0.384" diameter slugs were resized through the swaging machine to bring them back to round and to straighten them before annealing. They were annealed in fixtures which held them straight.

Electrocleaning:

Equipment used:

a. Seventy-five ampere rectifier
b. Ventilated plating bench equipped with a voltmeter, ammeter and rheostat
c. Three 600 ml beakers
d. Lead cathode
e. Platinum wire fixture

Materials

a. Electropolishing solution (46 v/o H_2SO_4, 9 v/o glycerine 45 v/o water)
b. Distilled water
c. Acetone
d. Cellulose tissue

Reaction of the hot uranium slugs with the quench water in beta treating caused a loose oxide film to be formed on the surface of the slugs which rubbed off and could not be accounted for after subsequent handling. After processing the first five castings an electrocleaning operation was added to the sequence following beta treating and alpha annealing. The same solutions were used for the final electropolishing, but for cleaning only the surface oxide was removed and no attempt was made to develop a polished surface. From six to nine volts were used depending upon the freshness of the solution. Current density was about five amperes per square inch. An insoluble film was left on the slugs which was wiped off with tissue. The slugs were water rinsed and dried with acetone. They were weighed and the weight loss credited to the electrocleaning residue.

Finish Machining:

Equipment used

a. Hooded Monarch EE-10" lathe
b. Carbide-tipped tool ground for facing, chamfering and burring
c. Micrometers
d. Lathe-carriage movement indicator
e. 23/64 collet

The slugs were next machined to finished length. One end was faced off and the edge given a 1/64"-45° chamfer. They were then measured and the second end faced to within about 0.010" of finished length. They were remeasured, machined to finished length, chamfered and burred. These operations were all carried out in a closed hood on the lathe using a boring bar tool ground for the combination of operations. The lathe was operated at about 300 rpm without coolant. After machining, the slugs and turnings were weighed and balanced against the total weight of electrocleaned slugs.

Dilatometer test::

Equipment used

a. Comparison dilatometer
b. Hot plate
c. 1500 ml beaker
d. Vacuum flask
e. Ring stand and burette clamp

Materials

a. Distilled water
b. Ice
c. Acetone

Coefficient of expansion in the direction of rolling was found to be a measure of the preferred orientation of the microstructure of the slugs. The coefficient of expansion of the alpha rolled and swaged uranium measured about $6.5 \times 10^{-6}/°C$. That of properly beta treated slugs measured between 13×10^{-6} and $15 \times 10^{-6}/°C$. This property was measured between 0°C and 100°C using a comparison dilatometer which showed the differential expansion between the uranium slug and nickel. The coefficient of expansion of the nickel used in the dilatometer was measured at $13.2 \times 10^{-6}/°C$.

The slug to be tested was placed in the dilatometer which was dipped in ice water to the immersion mark. After one minute, the dial was zeroed and the instrument transferred to boiling water. After the instrument reached equilibrium, it was read and the dilatometer returned to the ice water to check the zero setting. A maximum deflection at 100°C of +0.0003 to 0.0000 was allowed.

Dimensional inspection:

Equipment used

a. Comparator with 0-0.200" range by 0.0001" indicator head
b. Gage blocks (Johannson)

The machined slugs were assigned identifying numbers and were measured by comparing dimensionally with gage blocks using the comparator. Maximum and minimum diameters were obtained by rolling the slugs under the comparator tip against a stop. The slugs were then individually weighed and packaged in cellophane bags to be held for final loading into the fuel rods.

Electropolishing:

Immediately before loading into the fuel rods, each slug was electropolished using the same equipment and solutions as were used for electrocleaning. However, for polishing, the slugs were left in the solution long enough to produce a polished surface. After polishing each slug was rinsed through two changes of distilled water and dried in acetone. Care was taken to avoid contamination of the surfaces with anything which might interfere with wetting by the sodium-potassium alloy. Clean mortician's gloves were used to handle the slugs while they were weighed and loaded into the fuel rods. Figure 5 shows a slug ready for loading.

Assembly of the lower fuel rod sections:

Equipment used

a. Positioner made from standard laboratory apparatus clamps
b. Loading horn

Parts

Number Per Rod	Drawing Number	Description
1	EB 1137B	Rod trip
	EB 1133C	Fuel section tube
1	EB 1143B	#347 SS jacketed normal uranium blanket slugs, 4.750" long
5	EB 1136A	Slug spacers
4	EB 1138A	Enriched uranium fuel slugs, 1.872" long
1	EB 1144B	#347 SS jacketed normal uranium blanket slugs
1	EB 1140A	Spring seat
1	EB 1135A	Compression spring
1	EB 1134C	Bypass section
1	EB 1141A	Sealing screw

The rod tip was welded to the fuel section tube as it was received. The tube was clamped into the positioning fixture with the tip raised at about 45° to the horizontal. The loading horn was placed over the end of the rod and the lower blanket slug inserted into the tube. A spacer was then placed over the exposed end of the slug. An enriched slug was placed against the spacer and the assembly pushed up through the loading horn. This crimped the tabs on the spacer against the slugs. The procedure was repeated for each slug. When all of the slugs were in place, the rod tip was lowered and the spring seat, spring, and by-pass section were inserted. The by-pass section was lined up with the fins on the fuel section tube, then pressed down into the tube section. When properly dimensioned the by-pass section fitted the fuel section with a light press fit. The fuel rods were then radiographed to determine whether all slugs were in their proper positions, using a Co^{60} source.

A log was kept on the loading which showed the position in the rod, S. M. batch number, weight, calculated quantity of U^{235} and dimensions of each slug in the fuel rod. The location of the normal uranium and enriched uranium slugs in the fuel rod were designated as follows:

Position	Material	Part No.
1 (At bottom)	2 Normal U blanket slugs in stainless steel jacket 4.75" long	EB 1143B
2	Enriched uranium fuel slug	EB 1138A
3	Enriched uranium fuel slug	EB 1138A
4	Enriched uranium fuel slug	EB 1138A
5	Enriched uranium fuel slug	EB 1138A
6 (At top)	3 Normal U blanket slugs in stainless steel jacket 8" long	EB 1144B

The loading record is compiled as Appendix B[4] of this report.

The arrangement of parts in the fuel rod is shown in Figure 6. The spacers shown between each fuel slug and above each slug centered the slugs in the tube. The assembled fuel and by-pass sections are shown above the internal part view.

A rod number was etched into the by-pass section of each rod using an electro-etcher.

Welding, straightening, leak detecting and argon filling:

Equipment used

a. Direct current welding apparatus, argon shielded tungsten electrode type
b. Collet lathe geared down to 1-6 rpm
c. Arbor press
d. Straight edge and line-up fixture
e. Helium leak detector (General Electric)
f. Manifold for evacuation and argon filling

Materials

a. Helium
b. Welding grade argon
c. Purified and dried argon gas

The assembled fuel rod was placed in the lathe collet and the by-pass section welded to the fuel rod by burning down a small flange left for the purpose on the by-pass section. The welding set up is shown in Figure 7. The weld section before and after welding is shown in Figure 8.

After welding the fuel rods were hand straightened using an arbor press, checked against straight edges and finally tested by passing through a gage using broached holes similar to those in the reactor. The straightening press and gages are shown in Figure 9.

The final operation consisted of leak detecting with a helium-senitive mass-spectrometer, leak detector, argon-gas filling and sealing. This was done by fitting a gas-tight manifold over the end of the rod containing an argon-gas inlet and an evacuation outlet and an Allen wrench operated through a rubber packing. The fuel rod was first evacuated with an auxiliary pump and the valve connecting the leak detector opened. A shroud tube was placed over the fuel rod and this was filled with helium. If an indication was found the shroud tube was removed and the leak located by using a fine helium jet. Leaking welds were rewelded and retested. After leak detecting the valves to the leak detector and roughing pump were closed and purified argon gas was admitted to a pressure of about 4 pounds above atmospheric. The rod was then sealed by inserting and tightening the sealing set screw.

Deviations from process:

With the exceptions listed below, the process was carried out without deviation from that set forth in the process flow sequence (Figure 1). The exceptions were as follows:

Casting No.	Changes in Sequence & Reasons for Changes
16F16	The slugs fabricated from this casting showed minute, multiple, circumferential cracks. (See Figure 10) The analysis of these slugs showed an iron content of 500 ppm and a silicon content of 100 ppm. The buttons used were both high in iron and silicon, (page 138, Appendix A[3]). The slugs were returned to Oak Ridge for reprocessing. ✓ Delete

Casting No.	Changes in Sequence & Reasons for Changes
16F22	The upper end of this casting was cropped off before fabrication.
16F35 thru 16F42	These rods were fabricated to 0.383" -0.386" diameter rather than 0.363" to 0.364" diameter. They were first cut to 7.100" long and sent to Arco for in-pile tests. Later they were returned and cut to 2.515" long and assembled into fuel rods.
16F41, A & B	The stopper rod parted just above the molten metal line and this melt failed to pour, forming a solid mass of metal in the bottom of the crucible. This mass was remelted in a crucible without a stopper rod and the metal allowed to drip down into a water-cooled copper mold. This "casting" was then broken up and remelted and fabricated according to standard practice.

Quantity control and process data:

Equipment used

a. 2 kg capacity analytic balance
b. 200 g automatic analytic balance
c. Class S weights 1 g to 3 kg

Accurate control of the quantity of enriched uranium was required throughout the process. The material in process was weighed to the nearest milligram before and after each operation. Wherever possible, residues were weighed directly as in the case of machine cuttings. However, it was necessary to obtain residue quantities as difference figures where the uranium was collected in a form not immediately measurable, as in the case of uranium pick-up by the ceramics in melting, and uranium dissolved in the electropolishing solutions and remaining in the oil heating bath.

While an effort was made to process each batch the same to obtain uniformity of the finished fuel, small variations in the operations of the equipment and variations made necessary by incidents in the operation of this process were recorded. Results of the process weighings and conditions of operation were recorded on a series of mimeographed forms covering each operation in order that the similar information might be recorded on each batch of material processed. This data has been assembled as Appendix A[3] of this report.

The ANL Special Materials Department maintained an accounting office and vaults in the fissionable materials fabrication area keeping a running inventory of material processed and materials in process. Their information was cross correlated to the Metallurgy Process Data Record.

Table III is a resume´ of the Process Data Record showing the quantities of uranium melted in each batch of material, the quantities of uranium produced as finished fuel and the process residues on each batch of material processed. These are related to the quantity of reduction metal used (after sampling) as a percentage.

Table IV shows further information on the process residues, giving their approximate gross quantities and a description of the bulk materials transmitted to the vaults to be held for recovery. Process losses do not show up in this report and cannot be shown until such time as there is a complete material recovery. Melting residues and turnings have been recovered and returned to Y-12 as nitrate and oxide. In each case the stated quantity of uranium was within the margin of error of the assay and isotopic analyses. Delete

Table III

WEIGHTS OF CHARGE MATERIAL, RESIDUES AND FINISHED FUEL, ON FIRST EBR CHARGE

Casting No.	Batch No.	Reduction Metal Used	Remelt Stock	Sol'n	Total Charge	Casting Residue	Fab & Anneal Residue	Beta Treat Residue	Turnings	Polishing Solution	Other Residue	Remelt Stock	Finished Fuel Slugs
16F1	2-280	2378.428			2378.428	38.350	2.552	.099	51.363	1.973	.011	267.439	2016.641
2	2-285	2387.194			2387.194	22.919	2.277	.084	52.371	.841	.022	352.093	1956.587
3	2-287	2383.463			2383.463	34.385	2.273	.067	47.385	1.511	.093	330.086	1967.663
4	2-290	2384.964			2384.964	31.549	2.277	.088	57.003	1.724	.181	212.423	2079.719
5	2-291	2284.542			2284.542	20.318	2.429	.049	60.670	1.717	.048	182.169	2017.142
6	2-298	2186.407			2186.407	20.075	2.612	1.051	42.499	1.944	.071	327.190	1790.965
7	2-299	2189.272			2189.272	25.204	2.361	.159	38.602	2.078	.068	576.186	1544.614
8	2-300	2285.711			2285.711	28.174	2.265	.134	43.213	2.539	.118	419.586	1789.682
9	2-301	2386.852			2386.852	28.045	2.531	.156	51.885	2.471	(.006)	154.853	2146.917
10	2-302	2385.731			2385.731	32.526	2.898	.125	47.895	1.887	.034	272.192	2028.174
11	2-313	2285.374			2285.374	42.066	3.170	.070	44.113	1.769	.047	280.162	1913.977
12	2-314	1092.309	1100.049	1.570	2192.358	38.151	2.606	.170	51.506	2.532	.054	252.970	1844.369
13	2-315	2232.715			2232.715	30.154	2.257	.040	64.435	2.375	.009	243.896	1889.549
14	2-318	2385.194			2385.194	67.575	2.497	.075	50.059	1.432	.006	238.575	2024.975
15	2-317	1192.108	1176.283	.892	2368.391	32.684	2.576	.072	50.433	1.703	.005	254.880	2026.038
16	2-320	2370.047			2370.047	38.604	2.266	.072	45.564	1.639	.027	309.318	1972.557
17	2-326	2290.830			2290.830	38.036	1.923	.168	46.939	2.253	.015	174.577	2026.919
18	2-328	1186.839	1034.852	1.654	2221.691	33.397	1.661	.088	43.129	2.475	.021	256.890	1884.030
19	2-329	2170.415			2170.415	22.435	2.284	.132	43.616	2.289	.033	206.332	1893.294
20	2-331	2285.726			2285.726	24.248	1.874	.114	47.495	2.348	.012	205.684	2003.951
21	2-332	1194.904	989.901	.421	2184.805	34.872	1.593	.099	44.363	2.307	.021	155.155	1946.395
22	2-334	2366.117			2366.117	44.476	1.763	.126	48.465	3.290	.022	265.336	2002.639
23	2-336	1186.436	579.104	.331	1765.540	31.156	1.397	.070	40.407	1.469	.016	156.688	1534.337
24	2-340	1490.343	514.572	.408	2004.915	30.154	1.700	.080	45.094	1.481	.002	212.475	1713.929
25	2-341	1182.642	789.250	.402	1971.892	38.573	1.220	.043	43.259	1.636	.003	236.918	1650.240
35	2-395-1	2375.377			2375.377	22.607	2.932	.296	33.022	2.564	.001	165.732	2148.223
36	2-395-2	2374.165			2374.165	19.787	2.248	.153	36.952	2.672	.000	159.969	2152.384
37	2-400-1	2373.470			2373.470	32.014	4.651	.142	77.013	2.529	.010	360.041	1897.070
38	2-400-2	2169.879			2169.879	17.576	3.570	.133	62.325	2.024	(.002)	468.677	1615.576
39	2-400-3	2167.801			2167.801	21.383	1.991	.105	59.196	1.877	.000	187.837	1895.412
40	2-400-4	2176.724			2176.724	20.642	1.920	.142	60.058	1.535	.001	195.781	1896.645
41	2-403	362.273	1773.901	1.054	2136.174	73.231	2.169	.306	74.115	2.333	.074	364.259	1619.687
42	2-419	2172.939	481.158	.113	2654.097	45.591	2.840	.412	52.782	1.684			2322.054
42R	2-419												228.734
		66337.191	8439.070	6.845	74776.261	1080.957	77.583	5.120	1657.226	66.901	1.017	8446.369	63441.088
7 Sample				.221									
19 Sample				.253									
w/o of Red. Metal		100.000		.011		1.629	.117	.008	2.498	.100	.002		95.634

* Note: Number 16F42-R is excess stock in vault after completion of work.

Table IV

PROCESS RESIDUE

Operation	Grams of Uranium	w/o of Charged Reduction Metal	Description of Residue	Approx. Gross Quantity
Total Uranium	66337.191	100.000		
Charge Preparation	7.319	.011	Cleaning solution	
Casting Residue	1080.957	1.629	(Crucibles) (Shot & Skulls) (50% HNO_3 Tube Cleaning Kleenex)	56 kg 2 gal.
Fabricating &) Annealing)	77.583	.117	Heating Oil Pump Oil	20 gal. 3 gal.
Beta Treating	5.120	.008	Quench Water	20 gal.
Notching & Facing	1657.226	2.498	Turnings	
Electrocleaning) & Polishing)	66.901	.100	46% H_2SO_4-9% glycerine Rinse Water Kleenex	4 gal. 3 gal. 2-2gal. container
Other Residues	1.017	.002	Small quantities of uranium saved at points not covered above. Testing residue and unaccounted weight differences.	
Total Residue	2896.123	4.366		
Finished Fuel + 228.734 g Excess	63441.088	95.634		
Total	66337.211	100.000		

DIE-UPSETTING OF FUEL SLUGS FROM 0.364" DIAMETER TO 0.384" DIAMETER

After the original in-pile experiments, 137 of the 1.872" x 0.364" diameter slugs were returning from the EBR to be increased in diameter to 0.384". This was done by die-upsetting, swaging to round-up, re-beta-treating and coining to length. A length of 1.665" to 1.668" was required to give an over-all fuel length of 10" with six slugs.

Similar normal uranium fuel slugs were first upset to study the effects of axial compression on thermal cycling behavior. Table IVa shows the results obtained by R. M. Mayfield upon upset normal uranium slugs, "Woosher" cycled between 50° and 550°C, 5 minutes in 50°C zone, 5 minutes in 550°C zone, and 5 seconds transfer time.

Table IVa

EFFECT OF COMPRESSION DEFORMATION UPON THE DIMENSIONAL STABILITY OF BETA TREATED URANIUM

Rod No.	Treatment	Nominal Dimensions	Cycles	ΔL (inches)	ΔD (inches)	% ΔL	%ΔL in 100 Cycles
8	Beta Treated * and Annealed **	0.85 L x 0.364 D	450	-0.0026	+0.0048	-0.3	-0.07
12	Beta Treated	0.85 L x 0.364 D	450	+0.0021	+0.005	+0.2	+0.04
7	Beta Treated; Die Upset	1-2/3 L	550	-0.0193	+0.0073	-1.1	-0.2
8	12.8 - 13.4% at 300°C. Swaged	x	550	-0.0442	+0.0058	-2.6	-0.5
9	2.3 - 2.9% at R. T.	0.385 D	200	-0.0150	+0.0023	-0.9	-0.4
10			200	-0.0166	+0.0033	-1.0	-0.5
17	Beta Treated, Die Upset 11.8 -	1-2/3 L	350	+0.0201	+0.0009	+1.2	+0.3
18	12.5% at 300° C. Swaged 1.5 -	x	350	-0.0195	+0.0059	-1.2	-0.3
19	1.6% at R. T., annealed	0.385 D	350	-0.0121	+0.0041	-0.7	-0.2
20			350	-0.0004	+0.0016	Nil	Nil
11	Beta Treated, Die Upset 11.8 -	1-2/3 L	350	-0.0033	+0.014	-0.2	-0.06
12	12.4 at 300° C, Swaged 1.2 -	x	350	+0.0048	+0.0114	+0.3	+0.09
13	1.7 at R. T. Beta Treated,	0.385 D	350	Nil	+0.0022	Nil	Nil
14	annealed. Coined 0.7-1.1 at		350	-0.0041	+0.0030	-0.2	-0.06
	R. T.						

*Beta Treatment; 1/2 hour at 725°C, water quench.

**Anneal: 2 hours at 575°C, air cool.

Mayfield concludes that the deformations indicated were apparently sufficient to cause slight alterations in the orientation and/ or grain size of the beta treated structure resulting in changes in stability characteristics. The cycling results indicated that the die-upset slugs should be beta heat treated before use.

Equipment used

a. Double-acting upsetting die (see Figure 11)
b. 10 ton hydraulic arbor press
c. #4 swaging machine
d. 0.383" diameter swaging dies
e. Coining dies

The die used is shown in Figures 11 and 12. It consisted of a split cavity insert, wedged into a tapered container block. This assembly was mounted in a spring-floated die shoe. Pressure was exerted on the ends of the slugs by means of fitted pins and the hydraulic press.

On the first tests the slugs were heated to 300°C in a small oil bath. The die inserts and pins were heated on a hot plate and the slugs were pressed at 300°C, at about 5 tons (85,000 psi pin pressure). A wrinkle pattern was formed on the upset slugs from the entrapped oil.

Later it was found that the beta treated and annealed slugs could be upset without the wrinkles if the pressure was increased to about 105,000 psi and the slugs were pressed cold. This made manipulation of the die much simpler since it could be handled without gloves.

The slugs so pressed were found to be slightly barrel shaped, about 0.003" to 0.005" greater at the middle diameter than at the ends. They were not perfectly round because of a slight spreading of the split die. Both of these faults were corrected by rotary swaging through a 0.384" straight swaging die.

The slugs were then re-beta-treated by the argon-bomb, lead bath method. Beta treating caused the slugs to increase 0.010 to 0.015" in length and decrease in diameter about 0.001". This was opposite to the changes in dimension noted on slugs beta treated from rolled rods.

The resulting slugs varied in length from 1.670" to 1.690". They were then cold-coined back to 1.666" long using a die similar to the upsetting die but with pins shortened so that the die insert served as a stop. The length of the die was 3.000" and the combined length of the pins 1.336 allowing 0.001" to 0.002" for elastic spring-back of the slug. Six tons (105,000 psi) was used to coin the slugs.

After coining, the slugs were vacuum annealed at 575°C for two hours. They were then electropolished and assembled into fuel rods, with six upset slugs per rod.

Table V shows the weight of the fuel slugs after each step of the operation. Cold upsetting and swaging resulted in an average loss of less than 0.002 grams per slug. Beta treating caused a slight gain in weight due to oxidation which was removed by electropolishing. The dimensions of the die upset fuel slugs are shown in Table VI. Cold coining gave a very accurate length of slug. Diameters were within the specified 0.383" to 0.386" with five exceptions.

Table V

WEIGHT ACCOUNT OF CP-4 SLUGS, UPSET FROM 0.364" DIAMETER TO 0.384" DIAMETER

Orig. Rod No.	Batch No.	Etch No.	Wt. as Received	Weight Upset and Swaged	Wt. β-Treat and Sized	Weight Annealed	Weight As Coined	Weight As E. Polished
F-345-1	2-280-1	52	59.184	59.182	59.181	59.181	59.181	59.117
	2	53	59.003	59.001	59.003	59.003	59.002	58.940
	3	54	59.623	59.622	59.622	59.623	59.622	59.543
	4	55	59.111	59.108	59.107	59.107	59.106	59.032
F-345-5A	2-280-17	56	59.345	59.342	59.342	59.342	59.343	59.270
	18	57	59.128	59.125	59.126	59.126	59.126	59.070
	19	58	59.109	59.108	59.108	59.106	59.102	59.040
	20	59	59.323	59.322	59.322	59.322	59.322	59.270
F-345-8A	2-280-29	60	59.540	59.540	59.540	59.540	59.540	59.485
	30	61	59.086	59.076	59.087	59.087	59.087	59.035
	31	62	59.452	59.450	59.451	59.452	59.452	59.359
	32	63	59.309	59.307	59.304	59.303	59.302	59.235
F-345-18	2-287-5	64	59.793	59.793	59.794	59.795	59.795	59.757
	6	65	59.646	59.646	59.646	59.646	59.646	59.586
	7	66	59.805	59.804	59.804	59.805	59.805	59.751
	8	67	59.637	59.637	59.639	59.639	59.639	59.389
F-345-27	2-290-9	68	59.453	59.453	59.452	59.453	59.453	59.374
	10	69	59.655	59.655	59.655	59.655	59.654	59.590
	11	70	59.595	59.593	59.593	59.593	59.593	59.534
	12	71	59.491	59.488	59.489	59.489	59.489	59.433
F-345-32	2-290-29	72	59.184	59.184	59.185	59.186	59.186	59.117
	30	73	59.223	59.223	59.221	59.222	59.222	59.169
	31	74	59.291	59.291	59.290	59.291	59.291	59.232
	32	75	59.352	59.350	59.350	59.350	59.351	59.290
F-345-40	2-291-29	76	59.314	59.314	59.314	59.314	59.314	59.269
	30	77	59.400	59.400	59.400	59.400	59.399	59.326
	31	78	59.126	59.126	59.126	59.126	59.126	59.063
	32	79	59.358	59.357	59.356	59.357	59.358	59.312

Table V - (Contd.)

Orig. Rod No.	Batch No.	Etch No.	Wt. as Received	Weight Upset and Swaged	Wt. β-Treat and Sized	Weight Annealed	Weight As Coined	Weight As E. Polished
F-345-48	2-299-1	80	59.371	59.368	59.367	59.367	59.364	59.232
	2	81	59.280	59.278	59.278	59.278	59.278	59.196
	3	82	59.439	59.437	59.436	59.436	59.435	59.350
F-345-52	2-299-17	83	59.484	59.484	59.483	59.483	59.482	59.439
	18	84	59.586	59.586	59.586	59.586	59.585	59.555
	19	85	59.395	59.395	59.394	59.394	59.394	59.356
	20	86	59.446	59.438	59.430	59.430	59.429	59.373
F-345-53A	2-299-21	87	59.660	59.658	59.657	59.657	59.655	59.572
	22	88	59.349	59.347	59.347	59.347	59.346	59.274
	23	89	59.428	59.427	59.425	59.425	59.425	59.343
	25	90	59.263	59.263	59.261	59.261	59.260	59.189
F-345-60	2-300-27	91	59.214	59.214	59.214	59.215	59.212	59.184
	28	92	60.200	60.200	60.199	60.200	60.198	60.146
	29	93	59.321	59.321	59.321	59.321	59.320	59.255
	30	94	60.074	60.071	60.071	60.072	60.070	60.030
F-345-61	2-301-1	95	59.608	59.608	59.607	59.607	59.606	59.574
	2	96	59.770	59.770	59.770	59.770	59.768	59.707
	3	97	59.752	59.751	59.751	59.751	59.750	59.716
	4	98	59.486	59.484	59.484	59.485	59.483	59.452
F-345-66	2-301-21	99	60.014	60.011	60.011	60.011	60.010	59.971
	22	100	59.501	59.497	59.496	59.496	59.495	59.448
	23	101	59.649	59.646	59.646	59.647	59.645	59.601
	24	102	59.339	59.333	59.331	59.331	59.330	59.288
F-345-67A	2-301-25	103	59.528	59.528	59.527	59.527	59.526	59.483
	26	104	59.645	59.645	59.642	59.642	59.640	59.605
	28	105	59.563	59.560	59.559	59.560	59.558	59.508
	29	106	59.728	59.724	59.719	59.719	59.717	59.677
F-345-71	2-302-5	107	59.463	59.461	59.460	59.460	59.458	59.404
	6	108	59.767	59.766	59.765	59.765	59.764	59.716
	7	109	59.612	59.611	59.611	59.612	59.610	59.571
	8	110	59.578	59.578	59.578	59.579	59.578	59.504
F-345-74	2-302-17	111	59.709	59.709	59.709	59.709	59.707	59.652
	18	112	59.490	59.490	59.490	59.490	59.489	59.432
	19	113	59.495	59.495	59.495	59.495	59.494	59.458
	20	114	59.631	59.631	59.631	59.631	59.631	59.587
F-345-86	2-314-1	115	59.126	59.124	59.124	59.124	59.123	59.070
	2	116	59.740	59.740	59.737	59.737	59.737	59.689
	3	117	59.990	59.990	59.990	59.990	59.990	59.939
	4	118	59.874	59.874	59.873	59.873	59.874	58.830
F-345-87	2-314-5	119	59.857	59.856	59.856	59.856	59.856	59.796
	6	120	59.690	59.690	59.689	59.690	59.690	59.647
	8	121	59.628	59.628	59.627	59.627	59.627	59.587
	9	122	59.165	59.164	59.164	59.164	59.164	59.125
F-345-92	2-314-22	123	59.909	59.909	59.908	59.909	59.908	59.852
	23	124	59.734	59.733	59.733	59.736	59.735	59.675
	24	125	59.604	59.604	59.604	59.606	59.605	59.528
	25	126	59.145	59.143	59.143	59.145	59.145	59.080

Table V - (Contd.)

Orig. Rod No.	Batch No.	Etch. No.	Wt. as Received	Weight Upset and Swaged	Wt. β -Treat and Sized	Weight Annealed	Weight As Coined	Weight as E. Polished
F-345-98A	2-315-21	127	59.470	59.468	59.466	59.467	59.467	59.428
	22	128	59.343	59.340	59.339	59.339	59.339	59.305
	23	129	59.305	59.301	59.302	59.303	59.302	59.222
	24	130	59.477	59.474	59.473	59.473	59.473	59.401
F-345-102	2-318-5	131	59.755	59.751	59.750	59.751	59.751	59.708
	6	132	58.806	58.805	58.805	58.805	58.804	58.754
	7	133	59.634	59.631	59.629	59.630	59.630	59.564
	9	134	59.800	59.797	59.796	59.796	59.796	59.706
F-345-124	2-326-29	135	59.830	59.827	59.827	59.826	59.826	59.784
	30	136	59.976	59.972	59.973	59.974	59.970	59.906
	31	137	59.529	59.527	59.527	59.528	59.528	59.482
	32	138	59.764	59.763	59.762	59.762	59.762	59.706
F-345-134	2-329-5	139	59.281	59.280	59.281	59.281	59.282	59.221
	6	140	59.129	59.129	59.128	59.127	59.126	59.085
	7	141	59.349	59.348	59.344	59.344	59.343	59.280
	8	142	59.192	59.192	59.191	59.191	59.191	59.141
F-345-135	2-329-9	143	59.188	59.188	59.186	59.187	59.187	59.152
	10	144	59.151	59.148	59.148	59.148	59.148	59.095
	11	145	59.215	59.213	59.213	59.213	59.213	59.175
	12	146	59.219	59.215	59.215	59.217	59.216	59.153
F-345-139	2-329-26	147	59.701	59.700	59.700	59.702	59.702	59.626
	27	148	58.561	58.559	58.560	58.561	58.561	58.491
	29	149	59.831	59.817	59.818	59.818	59.818	59.767
F-345-140A	2-329-30	150	59.818	59.815	59.815	59.815	59.814	59.746
	31	151	58.520	58.517	58.518	58.518	58.518	58.441
	32	152	59.481	59.480	59.478	59.478	59.478	59.418
	33	153	59.059	59.058	59.056	59.056	59.055	58.993
F-345-147	2-331-25	154	58.909	58.909	58.909	58.909	58.909	58.850
	26	155	58.895	58.895	58.894	58.894	58.893	58.813
	27	156	58.959	58.959	58.958	58.958	58.957	58.875
	28	157	59.002	59.000	59.000	59.003	59.003	58.943
F-345-163A	2-334-25	158	59.067	59.067	59.067	59.067	59.067	58.998
	26	159	58.432	58.432	58.432	58.432	58.432	58.391
	27	160	59.294	59.294	59.294	59.293	59.294	59.226
	28	161	58.884	58.883	58.884	58.885	58.885	58.815
F-345-167	2-336-9	162	58.984	58.982	58.983	58.984	58.984	58.908
	10	163	59.062	59.061	59.061	59.062	59.061	58.995
	11	164	59.094	59.094	59.094	59.095	59.095	59.037
	12	165	59.043	59.043	59.043	59.044	59.044	58.974
F-345-169A	2-336-17	166	58.900	58.899	58.899	58.900	58.900	58.835
	18	167	58.977	58.975	58.976	58.977	58.977	58.904
	19	168	58.914	58.913	58.912	58.912	58.912	58.839
	20	169	59.028	59.026	59.026	59.026	59.026	58.949
F-345-170	2-336-21	170	59.060	59.059	59.059	59.059	59.059	58.999
	22	171	58.922	58.922	58.922	58.922	58.922	58.856
	23	172	58.746	58.746	58.746	58.746	58.746	58.643
	24	173	59.217	59.217	59.215	59.217	59.217	59.123

Table V - (Contd.)

Orig. Rod No.	Batch No.	Etch No.	Wt. as Received	Weight Upset and Swaged	Wt. β-Treat and Sized	Weight Annealed	Weight As Coined	Weight as E. Polished
F-345-174A	2-340-13	174	59.174	59.173	59.173	59.174	59.174	59.125
	14	175	59.076	59.076	59.075	59.076	59.075	59.013
	15	176	59.005	59.005	59.005	59.006	59.006	58.947
	16	177	59.155	59.154	59.154	59.155	59.155	59.103
F-345-191	2-341-20	178	59.080	59.079	59.079	59.081	59.081	59.000
	21	179	58.878	58.876	58.876	58.879	58.878	58.803
	22	180	59.002	59.000	59.000	59.001	59.001	58.922
	23	181	58.859	58.855	58.855	58.855	58.855	58.793
	2-280-33	182	59.314	59.313	59.315	59.315	59.315	59.258
	34	183	59.254	59.253	59.253	59.253	59.253	59.819
	2-285-33	184	59.285	59.284	59.285	59.287	59.287	59.224
	2-287-33	185	59.660	59.660	59.660	59.660	59.660	59.589
	2-290-34	186	59.174	59.173	59.171	59.171	59.170	59.080
	35	187	59.537	59.535	59.535	59.535	59.533	59.443
	2-341-28	188	58.785	58.772	58.771	58.770	58.769	58.692
	Total		8133.847	8132.636	8132.587	8132.642	8132.567	8123.788

Wt. account of upsetting, swaging and coining operations:

Upsetting & Swaging Residue	1.211 g
Beta Treating & Sizing	.049
Annealing & Coining	.020
Electropolishing	8.779
Total	10.059

Table VI

DIMENSIONS [TAKEN AFTER COINING] OF UPSET FUEL SLUGS

Etched No.	Batch No.	Diameter Min.	Diameter Max.	Length	Etched No.	Batch No.	Diameter Min.	Diameter Max.	Length
52	2-280-1	.3840	.3852	1.6657	101	2-301-23	.3855	.3858	1.6667
53	2	.3840	.3850	1.6648	102	24	.3845	.3847	1.6656
54	3	.3854	.3859	1.6662	103	2-301-25	.3843	.3857	1.6661
55	4	.3841	.3852	1.6652	104	26	.3853	.3856	1.6670
56	2-280-17	.3843	.3849	1.6658	105	28	.3859	.3861	1.6666
57	18	.3834	.3843	1.6676	106	29	.3851	.3865	1.6669
58	19	.3842	.3859	1.6672	107	2-302-5	.3853	.3856	1.6668
59	20	.3853	.3862	1.6682	108	6	.3863	.3866	1.6676
60	2-280-29	.3840	.3862	1.6679	109	7	.3862	.3869	1.6681
61	30	.3834	.3846	1.6657	110	8	.3871	.3864	1.6675
62	31	.3850	.3856	1.6677	111	2-302-17	.3855	.3861	1.6670
63	32	.3846	.3853	1.6675	112	18	.3845	.3860	1.6655
64	2-287-5	.3856	.3863	1.6667	113	19	.3845	.3859	1.6665
65	6	.3854	.3860	1.6650	114	20	.3853	.3855	1.6667
66	7	.3858	.3863	1.6667	115	2-314-1	.3839	.3845	1.6654
67	8	.3851	.3862	1.6672	116	2	.3853	.3870	1.6666
68	2-290-9	.3846	.3856	1.6652	117	3	.3862	.3865	1.6672
69	10	.3844	.3866	1.6665	118	4	.3862	.3864	1.6670
70	11	.3846	.3854	1.6680	119	2-314-5	.3861	.3864	1.6672
71	12	.3848	.3853	1.6661	120	6	.3855	.3860	1.6665
72	2-290-29	.3843	.3848	1.6652	121	8	.3851	.3857	1.6661
73	30	.3841	.3848	1.6649	122	9	.3842	.3844	1.6653
74	31	.3844	.3851	1.6675	123	2-314-22	.3860	.3862	1.6688
75	32	.3843	.3855	1.6668	124	23	.3856	.3861	1.6665
76	2-291-29	.3846	.3854	1.6670	125	24	.3854	.3856	1.6675
77	30	.3846	.3856	1.6670	126	25	.3840	.3842	1.6660
78	31	.3837	.3855	1.6650	127	2-315-21	.3855	.3858	1.6672
79	32	.3843	.3855	1.6668	128	22	.3844	.3852	1.6656
80	2-299-1	.3851	.3863	1.6674	129	23	.3843	.3851	1.6663
81	2	.3848	.3853	1.6673	130	24	.3852	.3858	1.6672
82	3	.3851	.3859	1.6651	131	2-318-5	.3855	.3861	1.6673
83	2-299-17	.3856	.3860	1.6656	132	6	.3835	.3838	1.6642
84	18	.3856	.3864	1.6678	133	7	.3859	.3861	1.6677
85	19	.3845	.3860	1.6678	134	9	.3861	.3864	1.6680
86	20	.3849	.3865	1.6677	135	2-326-29	.3870	.3865	1.6679
87	2-299-21	.3855	.3860	1.6680	136	30	.3862	.3867	1.6665
88	22	.3842	.3846	1.6665	137	31	.3853	.3855	1.6668
89	23	.3842	.3853	1.6680	138	32	.3863	.3865	1.6665
90	25	.3846	.3847	1.6665	139	2-329-5	.3844	.3848	1.6667
91	2-300-27	.3841	.3842	1.6650	140	6	.3841	.3848	1.6650
92	28	.3868	.3878	1.6673	141	7	.3847	.3851	1.6680
93	29	.3842	.3846	1.6665	142	8	.3841	.3846	1.6659
94	30	.3871	.3873	1.6658	143	2-329-9	.3857	.3864	1.6673
95	2-301-1	.3858	.3861	1.6664	144	10	.3851	.3856	1.6662
96	2	.3857	.3861	1.6665	145	11	.3849	.3853	1.6671
97	3	.3860	.3871	1.6672	146	12	.3849	.3851	1.6665
98	4	.3852	.3863	1.6673	147	2-329-26	.3858	.3860	1.6672
99	2-301-21	.3866	.3870	1.6680	148	27	.3840	.3843	1.6530
100	22	.3851	.3853	1.6665	149	29	.3860	.3863	1.6672

Table VI - (Contd.)

Etched No.	Batch No.	Diameter Min.	Diameter Max.	Length	Etched No.	Batch No.	Diameter Min.	Diameter Max.	Length
150	2-329-30	.3861	.3862	1.6667	170	2-336-21	.3842	.3843	1.6595
151	31	.3835	.3838	1.6615	171	22	.3841	.3842	1.6615
152	32	.3855	.3858	1.6678	172	23	.3842	.3843	1.6550
153	33	.3838	.3848	1.6673	173	24	.3846	.3847	1.6659
154	2-331-25	.3841	.3843	1.6591	174	2-340-13	.3840	.3844	1.6660
155	26	.3841	.3842	1.6604	175	14	.3842	.3844	1.6645
156	27	.3837	.3839	1.6638	176	15	.3838	.3843	1.6656
157	28	.3841	.3842	1.6644	177	16	.3843	.3844	1.6663
158	2-334-25	.3841	.3844	1.6640	178	2-341-20	.3836	.3845	1.6665
159	26	.3839	.3840	1.6500	179	2-341-21	.3838	.3841	1.6630
160	27	.3845	.3847	1.6654	180	22	.3840	.3842	1.6653
161	28	.3836	.3840	1.6628	181	23	.3837	.3840	1.6635
162	2-336-9	.3842	.3846	1.6665	182	2-280-33	.3842	.3847	1.6662
163	10	.3848	.3850	1.6648	183	34	.3842	.3847	1.6661
164	11	.3848	.3849	1.6661	184	2-285-33	.3845	.3848	1.6662
165	12	.3858	.3863	1.6664	185	2-287-33	.3851	.3854	1.6674
166	2-336-17	.3841	.3842	1.6668	186	2-290-34	.3836	.3839	1.6672
167	18	.3845	.3851	1.6674	187	35	.3846	.3851	1.6661
168	19	.3838	.3843	1.6668	188	2-341-28	.3834	.3837	1.6622
169	20	.3846	.3847	1.6675					

IGNITION OF TURNINGS FROM EBR FUEL FABRICATION

Of the residues formed in fabricating the EBR fuel, only the machine turnings and the crucible skulls were of sufficient purity for direct recovery. Tests were made with normal uranium on the use of turnings in casting charges. Because of the high surface-to-volume ratio of the turnings, this method was not found to be practicable. Therefore, it was necessary to convert the uranium to U_3O_8, in which form the material could be returned to the Y-12.

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Method:

Care was taken to prevent the contamination of the turnings. The method selected was to ignite them in a closed system under a helium-oxygen atmosphere followed by a six-hour heating under a welding oxygen atmosphere at 1000°C to effect a quantitative conversion to U_3O_8.

Equipment used

The following equipment was used on the job:

a. High-frequency-heated, horizontal ignition furnace
b. Porcelain ignition tube
c. High-frequency motor generator
d. Combustion boats
e. Oxygen and helium regulators
f. Exhaust gas washing bottles
g. Glove box
h. Sampling spoon
i. Oxide containers
j. 5 kg analytical balance
k. 200 g analytical balance
l. Platinum-10% rhodium thermocouple and potentiometer

The ignition furnace is shown in Figure 13. It consisted of a 4" I.D. x 30" ceramic tube over which was wound a 30 turn copper tubing induction coil. The assembly was supported in the outer transite shell by a diatomaceous earth packing. A 3-5/8" I.D. 0.060" wall x 25" long nickel tube was used in the ceramic tube as a heater.

A 3" I.D. closed end, porcelain combustion tube was used in the furnace. A water-cooled flange was fitted into this tube and it was closed by a cover plate fitted with an inlet for oxygen and an outlet for gas combustion products. The combustion tube assembly is shown in Figure 14.

The assembly was heated by power supplied by a 10,000 cycle, 15 KVA motor generator set. The first two ignitions were carried out in a platinum boat but it was found that the hot uranium alloyed with platinum and the remainder of the ignitions were done in slip-cast MgO oxide boats. Figure 15 shows combustion boat, platinum cover, ceramic oxygen induction tube and thermocouple used in the combustion tube. The boat was set in a platinum secondary container as a precaution against breakage and to provide a means of removing it from the combustion tube.

The effluent from the combustion was run through a settling bottle, a series of 3 gas washing bottles filled with distilled water, and was discharged into the ventilated glove box.

The combustion tube was assembled and disassembled in a standard ANL hood, Type 2, used as a glove box. The hood was modified to use combustible Waterman filter paper in the place of the glass filters usually supplied.

The oxide was transferred to standard "green salt" shipping containers. Samples were taken with a small platinum spoon.

<u>Procedure:</u>

The procedure was as follows:

1. The turnings were weighed from batches of known composition and a new batch composition calculated for the combustion charge. The charge was placed in the MgO combustion boat covered with the platinum cover and the assembly inserted into the combustion tube. The tube was sealed and placed in the induction furnace.

2. The furnace was heated to about 300°C using only a helium atmosphere.

3. Oxygen was slowly admitted as the ignition was viewed through the sight window. It was desirable to have the ignition proceed slowly enough that the turnings would ignite as separate particles rather than fusing down in the bottom of the boat and oxidizing as a clinker.

4. After the visibly violent reaction had ceased, the oxygen ratio was gradually increased to 100%. Steps 3 and 4 usually required about an hour.

5. The temperature was raised to 1000°C and held for six hours with a 100% O_2 atmosphere. (Flow of about 1/2 liter per minute)

6. The furnace was allowed to cool over night.

7. The combustion assembly was removed to the glove box, disassembled and the oxide carefully swept into tared containers.

8. The containers and oxide were weighed.

9. Samples were taken in tared weigh bottles.

10. Oxide and samples were weighed and given to the S. M. Representative for transmittal to the analytical laboratory.

11. Computations were made of the theoretical weight of U_3O_8 from the average atomic weight and compared with the weight of oxide produced.

The experimental work was done directly upon the enriched turnings using an initial batch of 44 grams. It was found necessary to hold the material at 1000°C for about 6 hours to obtain a weight increase equivalent to U_3O_8.

The method was found to be straight forward and presented no difficulties although it was time consuming.

Calculation of charges:

Since some variation in isotopic analysis was encountered, the average atomic weight was computed for each charge. The following chemical atomic weights were used for the calculations:

Symbol	Chemical
U^{234}	234.06
U^{235}	234.07
U^{238}	234.08

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Table VII

COMPUTED IGNITION CHARGES

Ignition Number	New Batch No.	Wt. of Turnings Ignited	U-234		U-235		U-238		Ave. A. W.
			w/o	Grams	w/o	Grams	w/o	Grams	
1	2-280E	44.412	0.94	.417	93.94	41.721	5.12	2.274	235.265
2	2-453	311.908	1.014	3.164	93.551	291.796	5.435	16.952	235.214
3	2-454	207.326	1.098	2.228	93.353	194.478	5.548	11.559	235.214
4	2-455	291.959	1.114	2.806	93.259	234.970	5.627	14.176	235.228
5	2-457	246.006	1.082	2.662	93.303	229.588	5.615	13.817	235.228
6	2-458	257.030	1.068	1.068	93.240	239.713	5.691	14.628	235.228
7	2-459	215.956	1.095	2.365	93.397	201.697	5.508	11.894	235.224
Total		1534.656	14.710		1433.963		85.300		

Table VIII

THEORETICAL AND ACTUAL WEIGHTS OF IGNITED U_3O_8

Ignition Number	Batch No.	Wt. of Turning Ignited Grams (a)	Theoretical U_3O_8 Grams (b)	Wt. of U_3O_8 from Turnings Grams (c)	Difference Grams (d)
1	2-280E	44.412	52.468	52.347	-.121
2	2-453	311.908	368.487	368.746	+.259
3	2-454	207.325	244.934	244.447	-.487
4	2-455	251.959	297.660	297.248	-.412
5	2-457	246.066	290.699	290.739	+.040
6	2-458	257.030	303.651	303.186	-.465
7	2-459	215.956	255.128	255.673	+.545
Total		1534.656	1813.027	1812.386	-.641

Completeness of reaction:

The over-all completeness of the reaction can be shown as a ratio of the oxygen.

$$\text{Per cent oxidation} = \left(\frac{\text{Actual oxygen}}{\text{Theoretical oxygen}}\right)\cdot 100$$

$$= \left(\frac{277.730}{278.371}\right) 100$$

$$= 99.77\%$$

Analytical data:

The samples submitted to the Special Material ~~Analytical~~ Group were assayed and analyzed isotopically. Results of the analyses and computation of net SF ~~material and~~ U-235 are shown in Table IX.

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Table IX

PER CENT URANIUM AND ISOTOPIC ANALYSIS

Igni-tion No.	Batch No.	(a) w/o U	(b) w/o U-234	(c) w/o U-235	(d) w/o U-238	(e) Calculated Wt. of SF Grams	(f) Calculated Wt. of U-235 Grams
1	2-280E	84.43 ± 0.10	0.93 ± 0.02	93.88 ± 0.05	5.19 ± 0.05	44.197 ± 0.052	41.492 ± .059
2	2-453	84.51 ± 0.10	1.01 ± 0.02	93.44 ± 0.05	5.55 ± 0.05	311.627 ± 0.368	291.184 ± .417
3	2-454	84.60 ± 0.10	1.11 ± 0.02	93.40 ± 0.05	5.49 ± 0.05	206.802 ± 0.244	193.153 ± .275
4	2-455	84.51 ± 0.10	1.11 ± 0.02	93.27 ± 0.05	5.62 ± 0.05	251.204 ± 0.297	234.298 ± .336
5	2-457	84.35 ± 0.10	1.08 ± 0.02	93.34 ± 0.05	5.58 ± 0.05	245.238 ± 0.291	228.905 ± .328
6	2-458	84.45 ± 0.10	1.07 ± 0.02	93.20 ± 0.05	5.73 ± 0.05	246.041 ± 0.303	238.630 ± .342
7	2-459	84.51 ± 0.10	1.06 ± 0.02	93.44 ± 0.05	5.50 ± 0.05	216.069 ± 0.255	201.895 ± .288
						1531.178 ±1.810	1429.557 ±2.045

Notes: Columns (a), (b), (c) and (d) from ANL-LFD-214.
Column (e) calculated as product of Column (a) from Table IX and Column (c) from Table VIII.
Column (f) is the product of Column (e) and Column (c) with the limits of error the root-mean-square of the limits shown in Columns (a) and (c).

Impurities:

Spectrographic analysis (ANL-LFD-225) gave the following data:

Table X

IMPURITIES IN PARTS PER MILLION

Delete

Element	Batch Number						
	2-280	2-453	2-454	2-455	2-457	2-458	2-459
Ag	3	2	1	1	2	3	4
Al	70	50	10	10	10	5	15
As	<10	<10	<10	<10	<10	<10	<10
B	0.5	0.5	0.2	0.2	0.2	0.2	0.3
Be	< 0.2	< 0.2	< 0.2	< 0.2	2	< 0.2	< 0.2
Bi	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Ca	<20	<20	<20	<20	<20	<20	<20
Co	< 5	< 5	< 5	< 5	< 5	< 5	< 5
Cr	5	1	2	2	1	1	10
Cu	20	10	5	15	20	10	10
Fe	200	100	100	200	100	50	500
K	<10	<10	<10	<10	<10	<10	<10
Li	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Mg	50	50	150	1000	200	100	500
Mn	3	3	3	3	5	2	5
Mo	<20	<20	<20	<20	<20	<20	<20
Na	2	2	7	5	< 2	2	5
Ni	10	50	10	20	10	10	20
P	<20	<20	<20	<20	<20	<20	<20
Pb	20	30	5	10	20	7	100
Sb	< 2	< 2	< 2	< 2	< 2	< 2	< 2
Si	1000	50	20	20	50	20	50
Sn	5	5	5	10	20	< 5	10
Ti	<50	<50	<50	<50	<50	<50	<50
Zn	<20	<20	<20	<20	<20	<20	<20

Table XI

WEIGHT ACCOUNT OF U-235 IGNITION

Ignition No.	1	2	3	4	5	6	7	
Batch No.	2-280-E	2-453	2-454	2-455	2-457	2-458	2-459	Total
Wt. of Turnings	44.412	311.908	207.325	251.959	246.066	257.030	215.956	1534.656
w/o U-235	93.94	93.551	93.353	93.259	93.303	93.240	93.397	--
Net U-235	41.721	291.796	194.478	234.970	229.588	239.713	201.697	1433.963
Total Oxide	52.347	368.746	244.447	297.248	290.739	303.186	255.673	1812.386
w/o Uranium	84.43	84.51	84.60	84.51	84.35	84.45	84.51	
Net Uranium	44.197	311.627	206.802	251.204	245.238	256.041	216.069	1531.178
% Enrichment	93.88	93.44	93.40	93.27	93.34	93.20	93.44	
Net U-235	41.492	291.184	193.153	234.298	228.905	238.630	201.895	1429.557
Oxide to Vault	51.675	368.076	243.806	296.586	290.070	302.507	255.005	1807.725
w/o Uranium	84.43	84.51	84.60	84.51	84.35	84.45	84.51	
Net Uranium	43.629	311.061	206.260	250.645	244.674	255.467	215.505	1527.241
% Enrichment	93.88	93.44	93.40	93.27	93.34	93.20	93.44	
Net U-235	40.958	290.655	192.647	233.777	228.578	238.095	201.368	1425.878
Oxide to Analysis	.672	.670	.641	.662	.669	.679	.668	4.661
w/o Uranium	84.43	84.51	84.60	84.51	84.35	84.45	84.51	
Net Uranium	.567	.566	.542	.559	.564	.573	.565	3.936
% Enrichment	93.88	93.44	93.40	93.27	93.34	93.20	93.44	
Net U-235	.532	.529	.506	.521	.526	.535	.528	3.680
Residue							Gain	
Uranium	.215	.281	.523	.755	.828	.989	(.115)	3.478
U-235	.202	.263	.488	.704	.772	.921	(.107)	3.350

Note: Calculations of samples after ignition are based upon mean analytical value without limits of error given in previous tables. Calculations before ignition are based upon computed values. Values may be off by amounts shown in Table IX. Table XI balances within the limit of error of the analytical data.

Residue:

The residue from this operation consisted of the following:

1. Five MgO ignition boats
2. Two beakers of gloves and cleanex
3. One bottle of 50% HNO_3 used to clean up platinum boat

All of the material was returned to the vault for disposal by the Special Materials Dept.

CONCLUSIONS

While the sequence of operations described in this report was followed without mishap or great difficulty, simplification of the process would be desirable. It would be particularly advantageous to eliminate those steps producing large volumes of difficultly recovered lean residues, such as the heating oil and wiping cloths used in rolling and swaging.

A method which might greatly simplify the procedure would be by the direct production of fuel slugs by casting. This would eliminate the fabricating oils and cloths. If suitable surfaces and structures could be produced, it would also eliminate the residues from beta treating and electropolishing. The casting residues and turnings can be recovered by comparatively simple methods. In addition to the savings in residue, the production of fuel slugs could be carried out by much less expensive equipment at a savings of time and effort.

The fractures in the slugs fabricated from casting number 16F16 seemed to indicate the need to control the purity of the metal from a fabrication standpoint, although additional experimental evidence is needed to determine how much silicon or iron can be tolerated.

ACKNOWLEDGEMENT

The completion of this project was the result of the whole-hearted cooperation and team work of many individuals in different divisions of the Laboratory. Credit is due to the design and shops sections of the Central Shops Division for their assistance in construction of the special equipment used; to members of the Foundry and Fabrication Group under Robert Macherey for fabrication of the normal uranium slugs and for valuable ideas on founding and fabricating methods.

Special credit is given to W. H. Morris for assistance in founding and fabricating the enriched uranium, to A. P. Hryn and B. J. McCollam for assistance in machining and fuel rod assembly, to C. T. Szymko for welding, and to J. M. Stack and Doris Mooney for Special Materials accounting. Isotopic analyses were made by C. M. Stevens and A. L. Harkness of the Special Materials Analytical Group under L. F. Dobry. Spectrochemical analyses were made by J. A. Goleb and F. S. Tomkins of the Chemistry Division. Thermal cycling tests were made by R. M. Mayfield and S. T. Zegler.

The fuel rods were designed by the EBR Program Group under direction of W. H. Zinn, Laboratory Director, and H. V. Lichtenberger, EBR Project Engineer.

The fabrication problem was carried out, from start to finish, under the guidance of F. G. Foote, Metallurgy Division Director, and J. F. Schumar, Associate Metallurgy Division Director, both of whom contributed valuable ideas and encouragement to the program.

REFERENCES

1. Shuck, A. B., Development of Methods for Casting and Fabricating Enriched Uranium Fuel Slugs; ANL-4617, 18 April 1951.

2. Kelman, L. R., "Dimensional Changes in Uranium Under Thermal Cycling," TID-68, Journal of Metallurgy and Ceramics, Vol. 4, pp. 3-36 (1949).

3. ANL-4847, Appendix A. Process Data. Issued separately to this report, three copies only.

4. ANL-4847, Appendix B. Fuel Rod Record. Issued separately to this report, three copies only.

Flow Sheet of Operations for Manufacturing Fuel Slugs

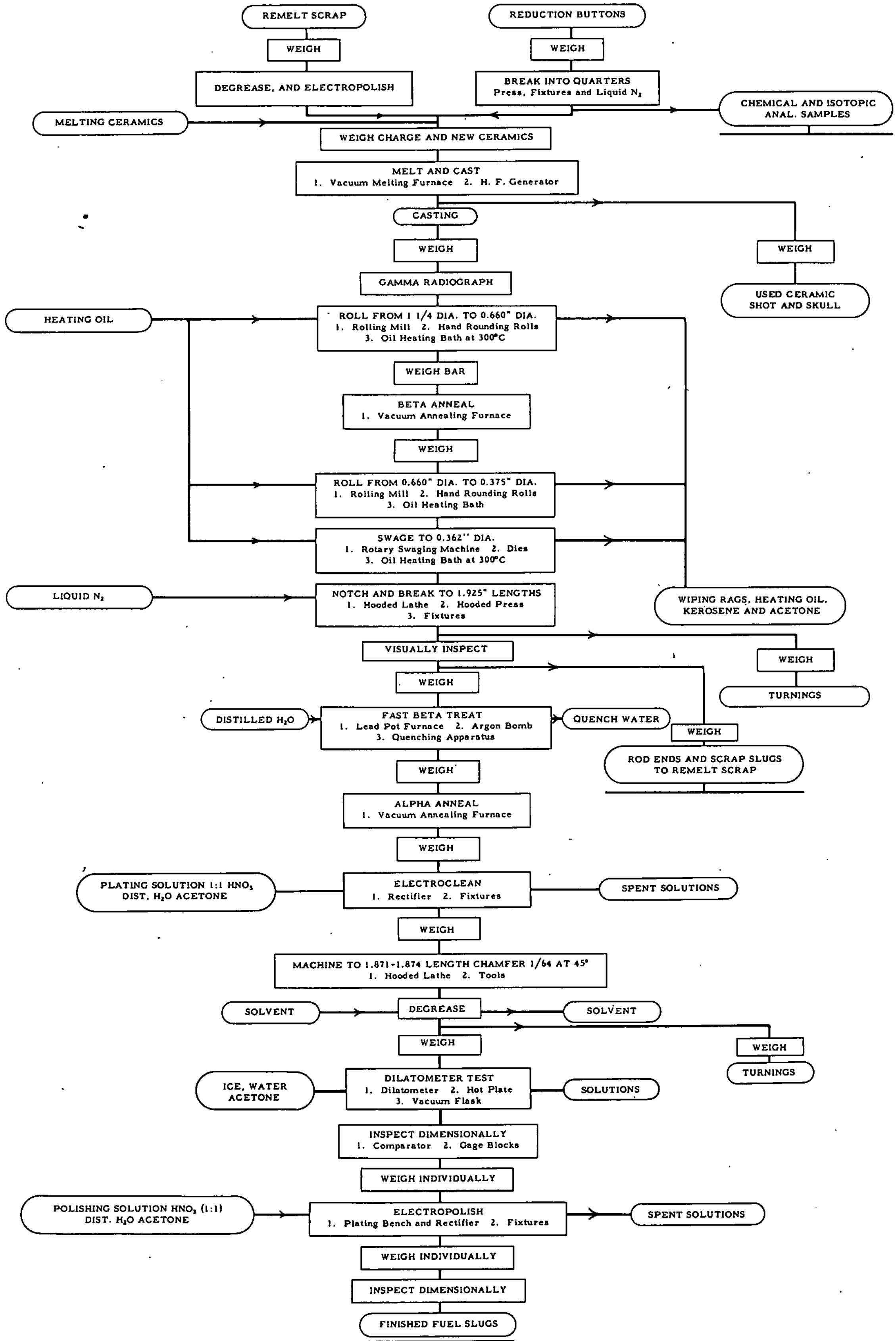
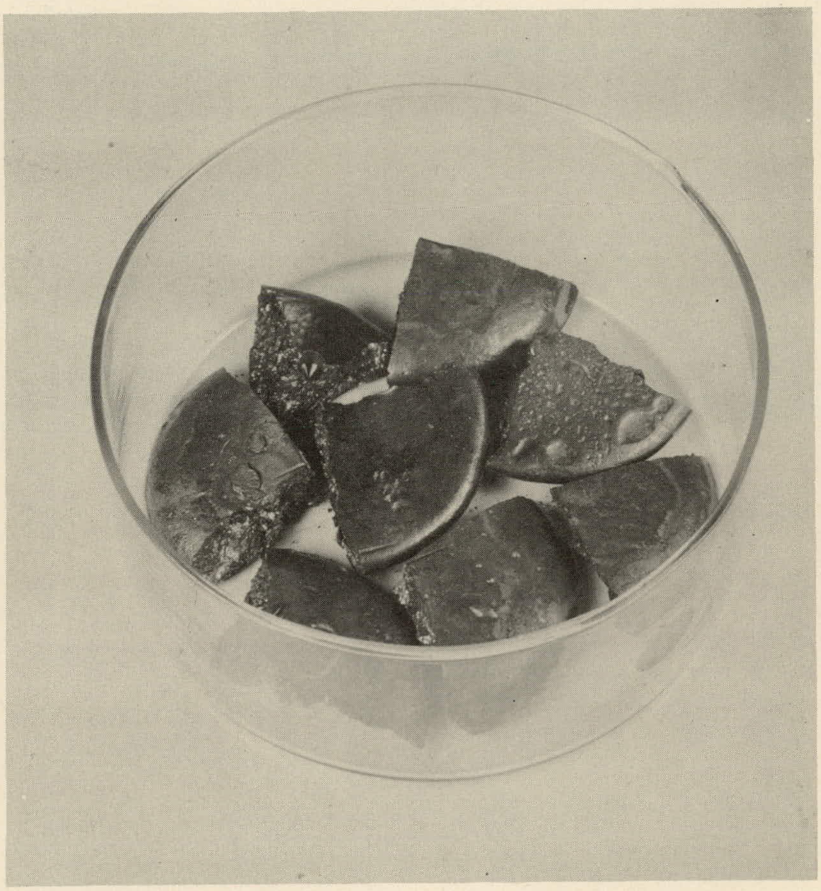


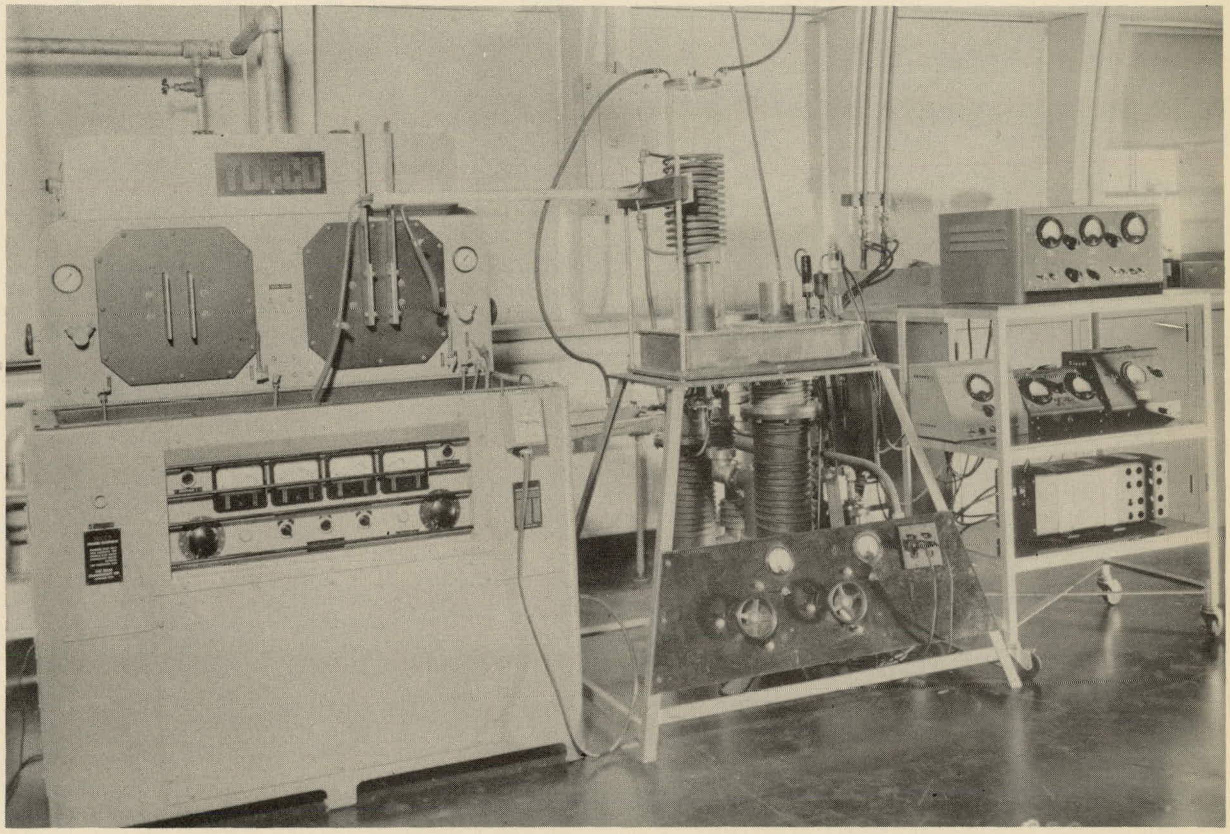
Figure 1

Figure 2. **Broken Reduction Button.**



AS-24 1/2 X
Reduction Button Broken and Sampled to be Melted

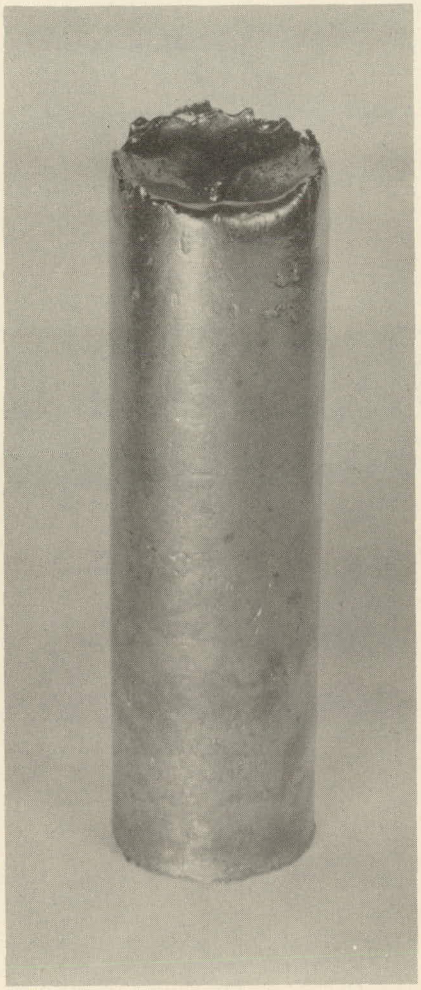
Figure 3. **Melting Furnace.**



AS-2

Furnace Used to Melt Enriched Uranium

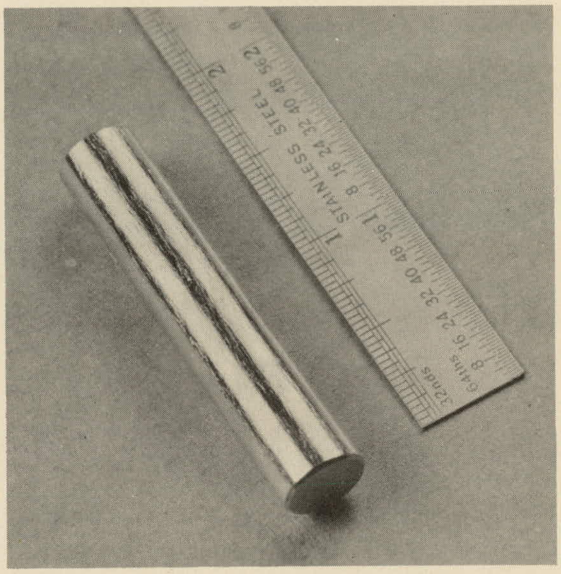
Figure 4. Enriched Uranium Casting.



AS-6

Enriched Casting Made in Water-Cooled
Copper Permanent Mold

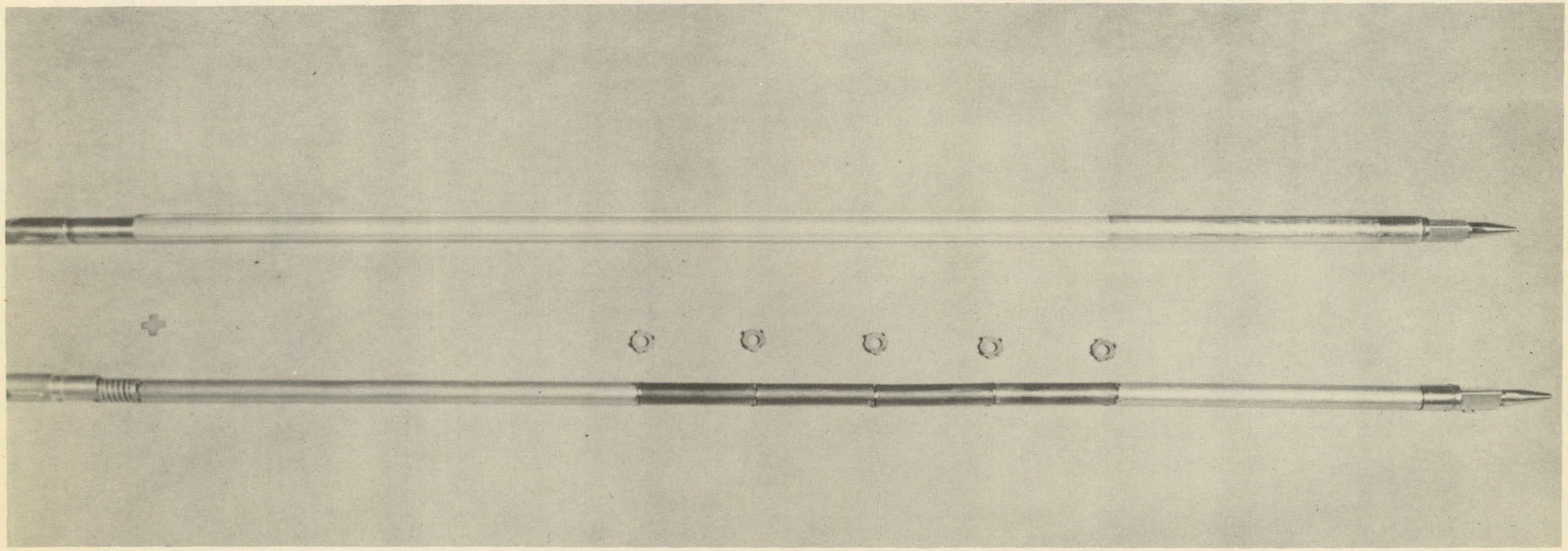
Figure 5. **Electropolished Fuel Slug.**



A^S-21 1 x

Fuel Slug After Electropolishing and Ready for Loading into Fuel Rod

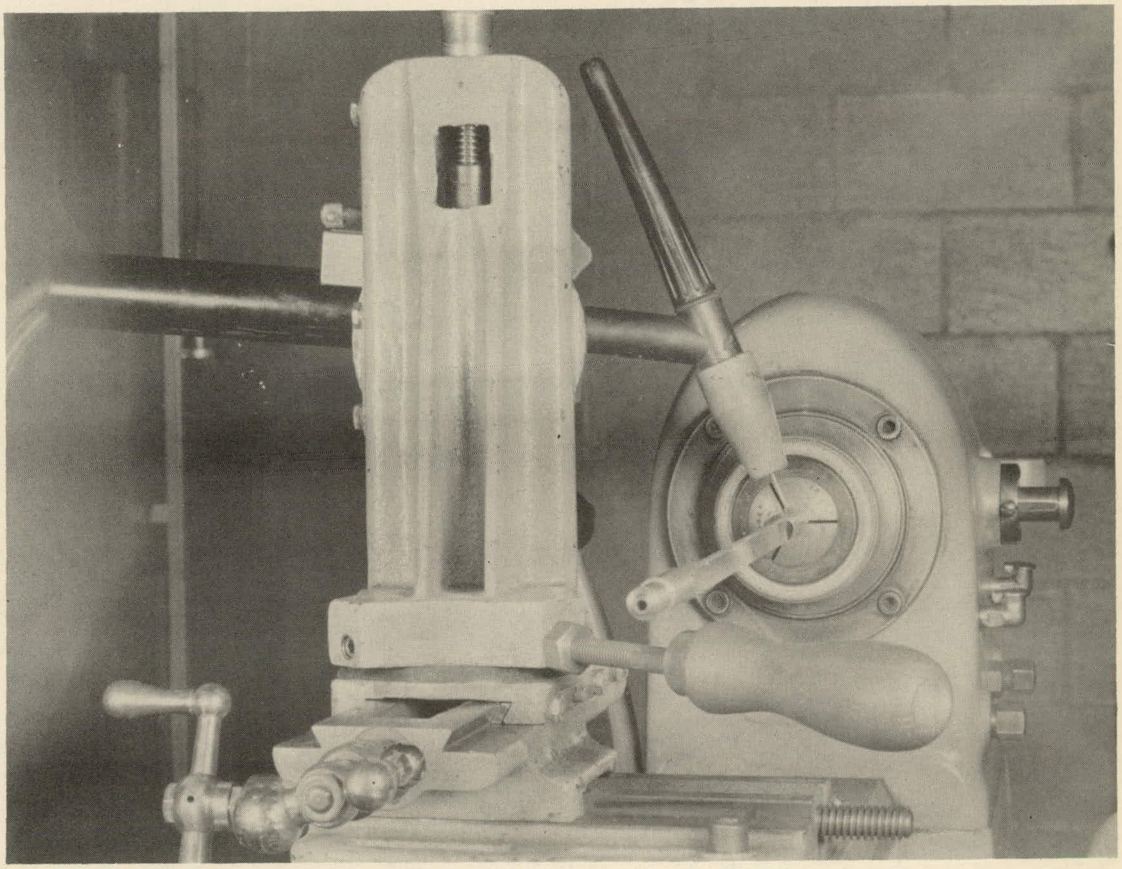
Figure 6. EBR Fuel Rod Assembly.



AS-28A 3/8 X

Upper rod is the assembled and welded fuel rod. Below it is the fuel slug assembly as inserted into the fuel tube. The spacers are shown above the fuel slug junction.

Figure 7. **Welding of By-pass Section.**



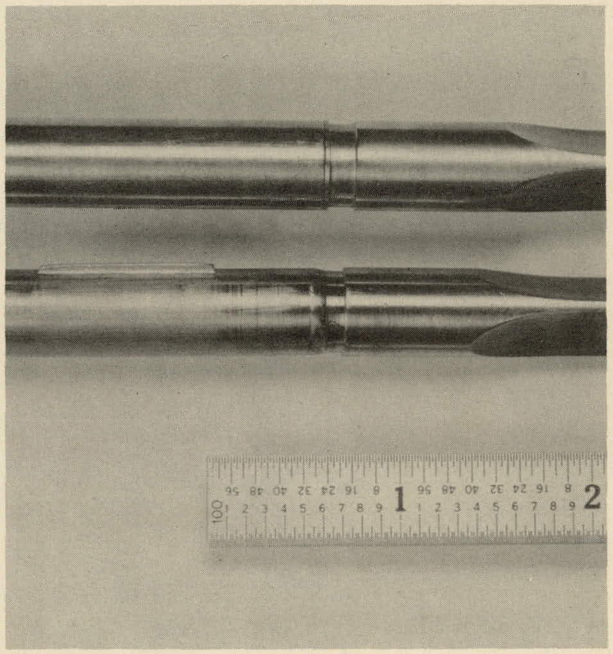
AS-29

Method of Welding By-pass Section to Fuel Section

Figure 8. **By-pass Weld.**

Fuel Section | **By-pass section before welding**

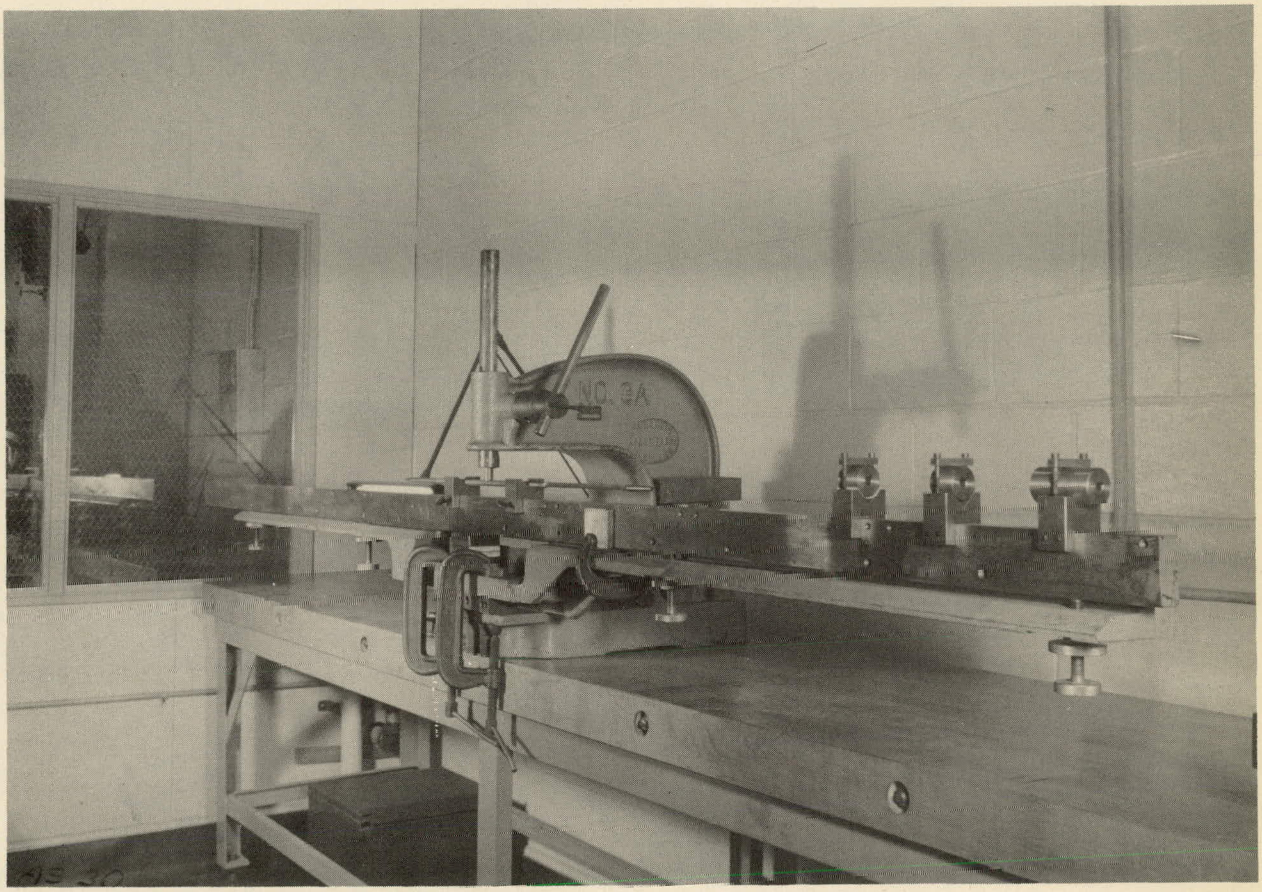
Fuel Section | **By-pass section after welding**



AS-127 1 X

Weld Between By-pass Section and Fuel Section of Fuel Rod

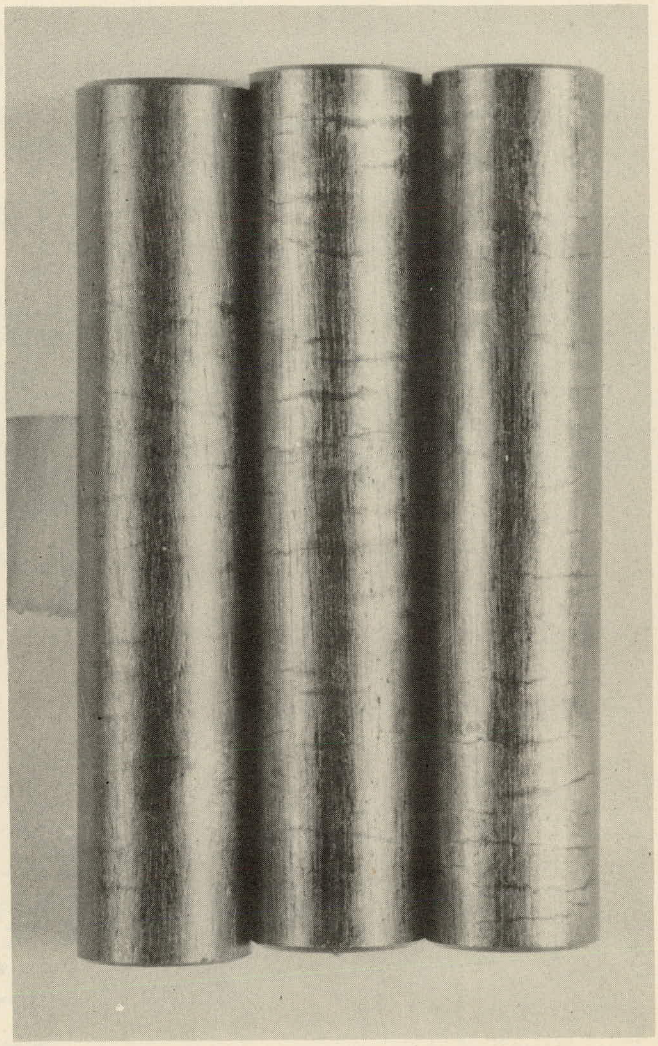
Figure 9. **Fuel Rod Straightener.**



As-30

Press and Gages Used to Straighten Fuel Rods

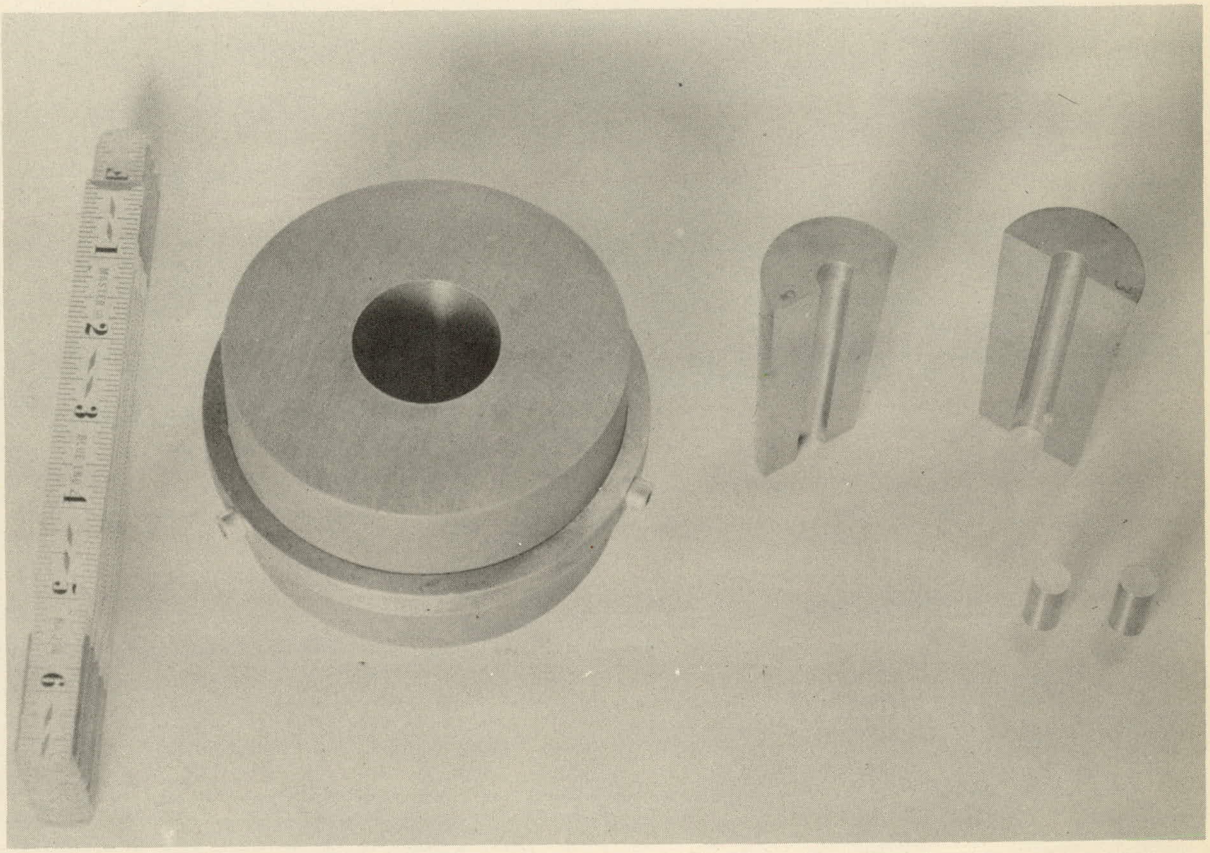
Figure 10. **Cracked Fuel Slugs.**



AS-27 2-1/2 X

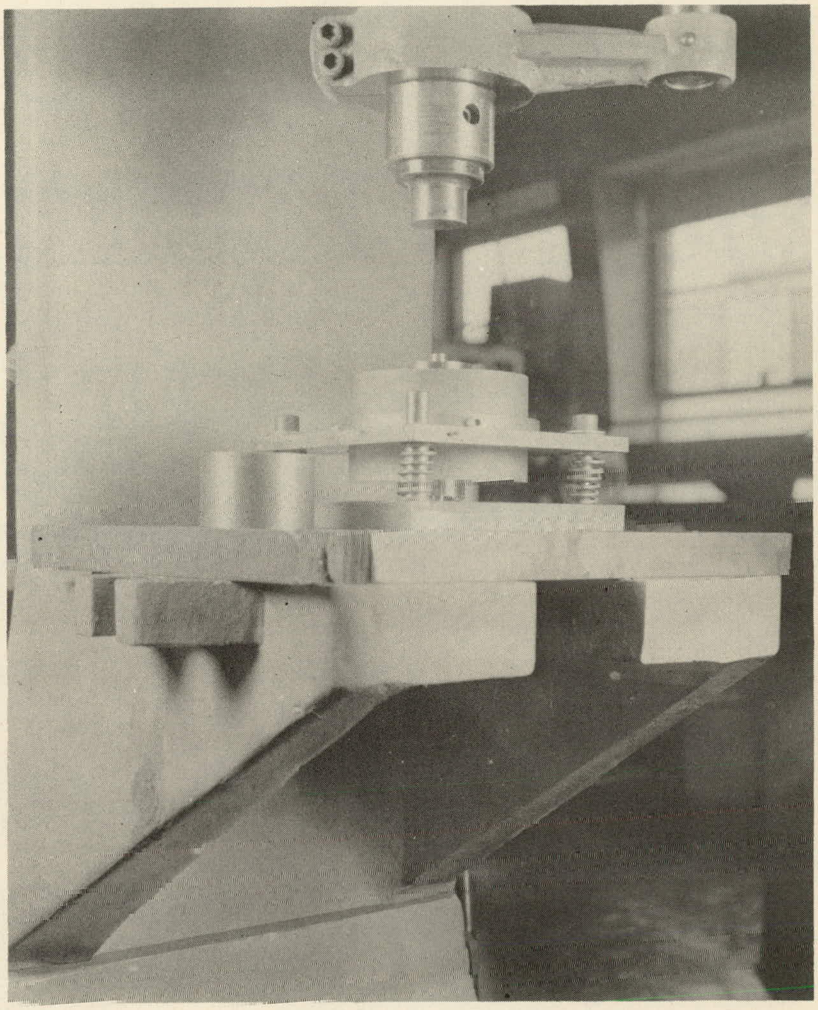
Cracks in Fuel Slugs from 16F16 Analyzing 500 ppm Fe and 100 ppm Si

Figure 11. **Upsetting Tools.**



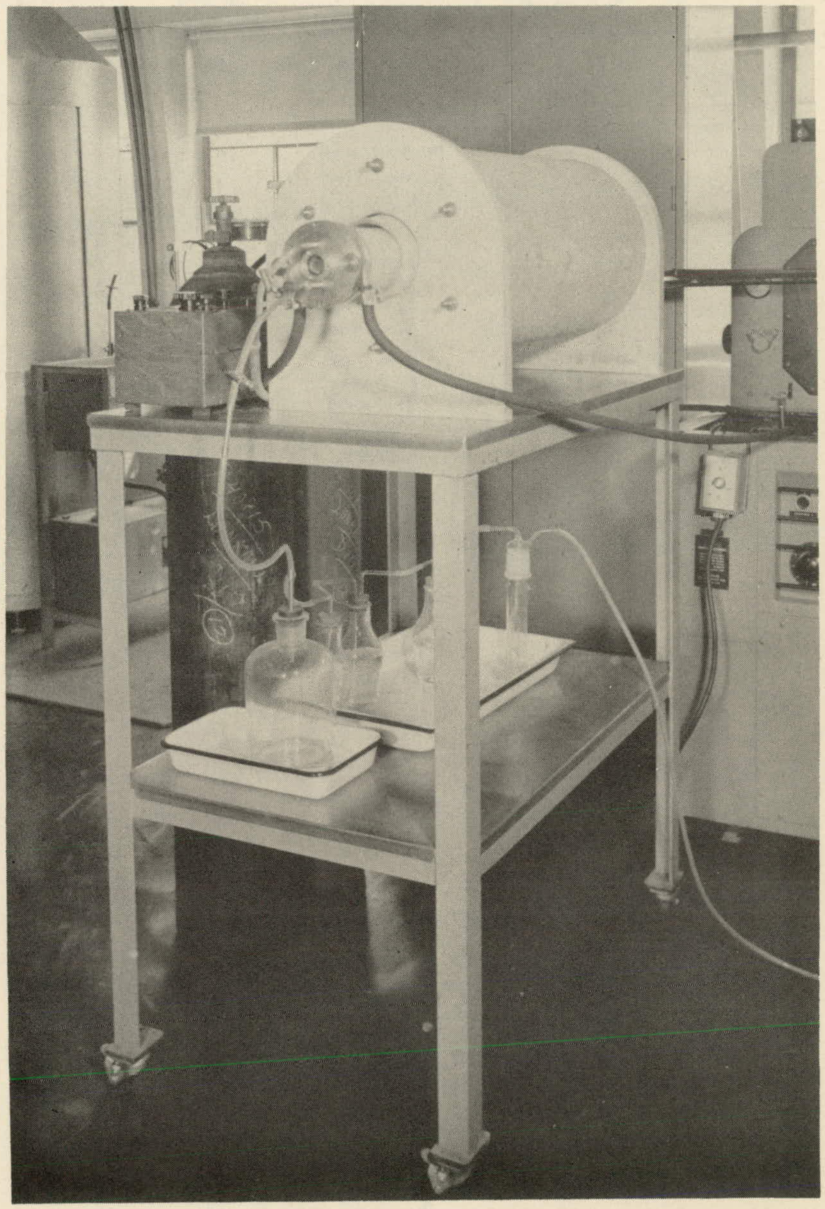
AS-63
Double Acting Dies, Pins and Container Used to Upset Fuel Slugs

Figure 12. **Upsetting Operation.**



AS-64
Die Assembled and in Press for Upsetting Operations

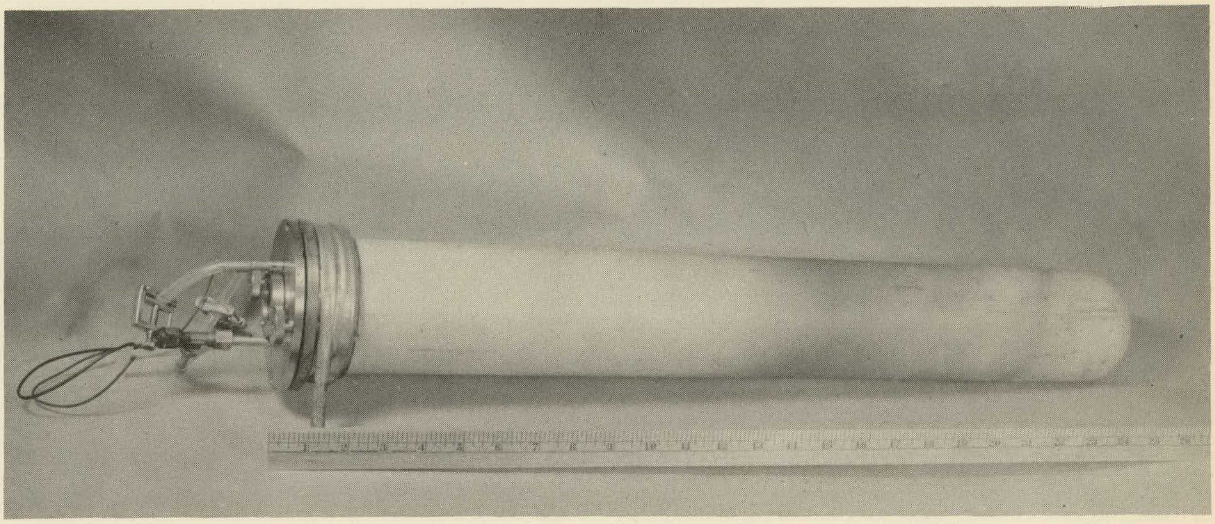
Figure 13. **Ignition Furnace.**



AS-97

Induction Furnace for Ignition of Turnings

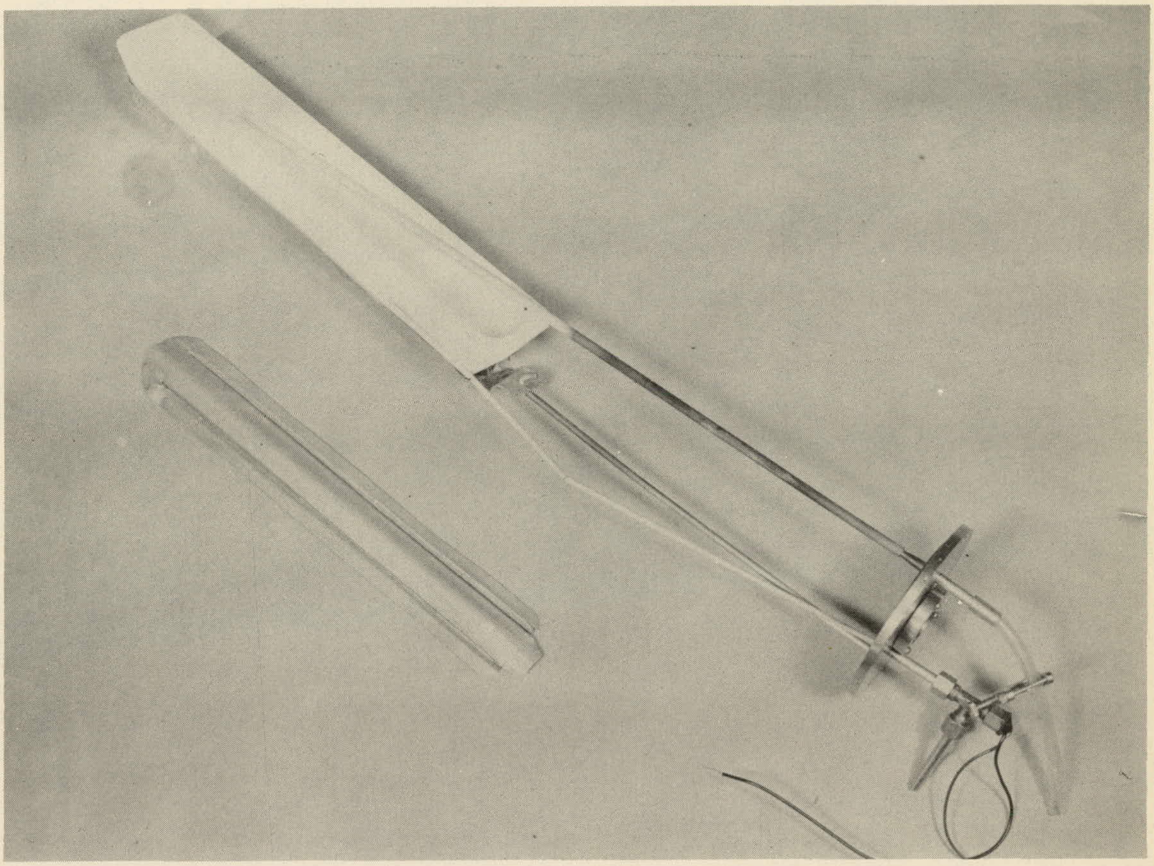
Figure 14. **Ignition Tube.**



AS-92

Porcelain Tube Used in Turning Ignition

Figure 15. **Ignition Boat Assembly.**



AS-91

MgO Boat Used in ignition furnace, showing arrangement of oxygen induction tube and thermocouple. The platinum cover was used over the MgO Boat.