DEVELOPMENT AND PRODUCTION
OF URANIUM 10 WT % MOLYBDENUM
AS-CAST SLUGS FOR HNPf PHYSICS EXPERIMENT

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ABSTRACT

A multiple casting process has been developed for the production of 0.590 ± 0.005 -in. diam by 12-in. long solid right cylinders. The process involves vacuum induction melting in MgZrO_3 coated graphite crucibles and casting into coated graphite molds. Thirty-eight hundred and fifty 90 wt % uranium of 3.5 wt % enrichment - 10 wt % molybdenum as-cast pins have been produced for Hallam Nuclear Power Facilities (HNPF) Exponential Experiments.

Figure 1. Mold Design for 44 Holes in ATJ Solid Graphite

I. INTRODUCTION

The experimental and production use of enriched uranium metal for reactor fuels makes it important that there be made available methods for its fabrication. Furthermore, it is desirable that the fabrication methods be relatively simple and economical, particularly when enriched uranium materials are involved.

The objective of this investigation was to develop such a process and subsequently produce sound as-cast 0.590-in. diam, 12-in. long solid-right-cylinder slugs of enriched U - 10 wt % Mo.

II. EXPERIMENTAL

A. CRITICALITY

Observations of the gravity static casting methods with vacuum induction techniques in use with normal uranium indicated that criticality safety factors would influence any mold concept relating to the casting of identical shapes of slightly enriched uranium into graphite. Conceptual mold configurations with forty-four and ninety 0.603-in. diam holes in solid graphite were considered and submitted for criticality studies (Figures 1 and 2).

Calculated results^{*} for criticality-safety criteria showed that unit molds of forty-four or a maximum unit of ninety[†] 0.603-in. diam holes in graphite could be used providing basic criteria could be firmly established, i. e., that the spatial distribution of the cast pins in the graphite molds could be reasonably uniform, that the cast pin axes could be parallel, and that the ratio of graphite volume to cast metal volume would not be greater than ten. Both the 44- and 90-hole mold concepts were found to be in accord with acceptable criticality criteria. A feasibility report was written and accepted^{*}.

B. CASTING ASSEMBLY

Fundamentally, the making of a mold for a casting is the shaping of a suitable material so that a liquid metal introduced into it will, after solidification, retain the shape predicted and can then be separated from it. This sounds

* J. A. Stanley, "Feasibility Report for Hallam Experimental Fuel Fabrication, NAA-TDR-4200 (July 29, 1959)

† J. A. Stanley and K. E. Buttrey, "Addendum to Feasibility Report for Hallam Exponential Fuel Fabrication," NAA-TDR-4316 (August 28, 1959)

Figure 2. Design for 90 Holes in ATJ Solid Graphite

simple, but when the material to be cast is molten uranium, certain very definite characteristics are demanded of the mold. These characteristics are:

- 1) The mold must be strong enough in its construction to sustain the weight of the metal.
- 2) It must be of such material as not to be seriously affected by the high temperature of uranium.
- 3) It must resist the cutting action of a rapidly moving stream of intensely hot metal during pouring.
- 4) It must be of such material as will cleanly strip away from the casting after cooling.
- 5) The surface finish of slugs must be usable without machining.

These stipulations so narrow the field of possibilities that there remains at present only one economical permanent mold material that can be successfully used: namely, a fairly dense graphite of low gas content.

1. Graphite for Mold Construction

Basically, graphite materials for mold construction should have good thermal conductivity, low thermal expansion, good strength at elevated temperatures, easy machinability to close tolerances, and low gas content.

The machining characteristics and gas content were experimentally determined for various grades of graphite. On the basis of these tests alone, ATJ type graphite was considered a mandatory material for mold construction.

2. Graphite Machining

Since close dimensional tolerances for warpage and diameter of each cast pin were required, it was necessary to machine each hole in the multiple cavity mold to close axis parallelism and diameter tolerances. Moreover, good surface of the individual hole in the graphite mold was necessary to insure good casting performance and mold life.

Several machining techniques were investigated and the best method found for sizing holes in graphite was simply to drill and to ream the holes on

Figure 3. Machining of 90-Cavity Graphite Mold

Figure 4. Casting Assemblies for 44- and 90-Hole Mold Units

a horizontal lathe with a modified mill indexer (Figure 3). Excessive tool wear and poor surface were characteristic of graphite materials other than ATJ grade.

3. Gas Content

Although the porosity content or density of CMD, CS, Speer 872TS, etc., graphite grades were approximately the same as ATJ (1.7 g/cc), excessive outgassing in the order of 4 to 1 was experimentally determined when compared to ATJ. Experimentally, graphite materials of excessive gas content were tried and poor results in regard to mold life and quality of casting were obtained.

4. Gating

The casting variable considered of primary importance is gating. It affects the pouring rate, fluidity, skin formation, turbulence, and mold erosion. Satisfactory gating for the individual holes in the 44- and 90-hole molds was achieved with the graphite distributors shown in Figure 4.

The ratio of the area of the pour hole in the crucible to the total area of the holes in the distributor is the gating. This is simply defined as:

$$\text{Gating Ratio} = \frac{A_1}{A_2}$$

where

A_1 = area of hole in crucible

A_2 = total area of holes in distributor

Experimentally, the best ratio found was 1.2 to 1.0 and used for both the 44- and 90-mold designs. However, for this ratio to deliver good results, particularly in regard to fluidity, it was found that the ambient distributor temperature had to be as high as the pour temperature (1395 to 1400°C). If this temperature was not maintained for at least 45 sec during pour, metal would plug

each hole in the distributor and freeze or cold shuts would result. Conditions such as these were investigated with the experimental gating and casting design shown in Figure 5.

Figure 5. Experimental Casting Vehicle

C. MOLDING

It must be emphasized in the founding of metals, the larger the mass and smaller the length to diameter ratio of the casting, the easier it is to achieve good castings. Obviously, the length to diameter ratio of 40:1 is not ideal. In addition, the mass of individual cast pin was less than 1 kg. Since this is considered a solidification problem it was decided to design for multiplicity of castings in solid graphite to increase the mass effect and use a heated mold to insure gradual solidification. Graphite molds which met these conditions are shown in Figure 4.

Moreover, it was found that details such as mold wash application, drying, baking, out-gassing and profile temperature of the mold, had to be carefully controlled or defective castings resulted. To insure reproducibility of the as-cast product, a definite procedure for casting was established. The procedure is as follows:

- 1) Only ATJ graphite material must be used for mold construction.
- 2) Refractory mold wash consisting of magnesium zirconate with sodium silicate as a binder must be used on all graphite components.
- 3) Prepared mold assemblies must be dried and baked at 450°F for a minimum of 12 hr in a controlled oven.
- 4) Graphite casting assembly must be out-gassed in vacuum for at least 45 min at 1000°C temperature.
- 5) The temperature profile of the 14-in. long graphite mold must be 1350°F at the lower end with a ΔT of 200°F for each 4-in. increment thereafter to the top of the mold.
- 6) Molds must not be immersed in any water bath.

D. MELTING

Alloyed uranium for fuel slug castings was inductively melted in vacuum, in refractory coated-graphite crucibles, and bottom poured into specially designed distributors and molds (Figure 4). Compatibility studies; such as maintaining metal purity with various ceramic washes on graphite crucibles, dissolution rates of the alloy metal in the molten uranium, and fluidity characteristics of the alloy, were achieved with the previously used test vehicle (Figure 5).

Certain characteristics of uranium melting and alloying which are important are:

- 1) Molybdenum metal powder pellets of approximately 1/2-in. diam by 3/16-in. thick of purity content shown in Table I should be used for alloying.

- 2) Uranium derby material of purity levels, as indicated in Table II, must be used for major constituent in alloy.
- 3) A 90 to 120 min residence at 1300°C temperature is considered the optimum condition for achieving good dissolution of the molybdenum, and control of carbon in molten uranium.
- 4) Unit composite charges of 50 wt % virgin materials of 50 wt % single remelttable scrap is considered a maximum dilution to control carbon to acceptable levels.
- 5) A 100 wt % double remelt scrap charge, i.e., reject slugs, risers, crop ends, etc. should be avoided.
- 6) Graphite crucibles must be heavily coated with magnesium zirconate to prevent carbon pickup during the melting cycle.
- 7) Graphite crucibles should never be immersed in any water bath.
- 8) A pour temperature range of 1395 to 1420°C must be maintained to insure good fluidity.

TABLE I
CHEMICAL COMPOSITION OF MOLYBDENUM PELLETS

Element	wt %	Element	wt %
Molybdenum	99.80 min	Nickel	0.02
Tungsten	0.02 max	Copper	0.010
Carbon	0.03 max	Silver	0.002
Oxygen	0.10	NVM*	0.10
Silicon	0.02	Hydrogen	10 ppm
Iron	0.02	Nitrogen	20 ppm
Total Impurities 0.20			

*NVM - Nonvolatile material in chlorine

Various methods for temperature observations were used such as; time, temperature, and power input cycles, mold temperature cycles, and optical pyrometry. Optical readings proved satisfactory. A typical melting and casting cycle, as shown in Table III, was considered satisfactory.

TABLE II

CHEMICAL COMPOSITION OF ENRICHED URANIUM DERBY MATERIALS

Element	Maximum Specification (ppm)	Element	Maximum Specification (ppm)
Boron	0.35	Iron	150
Cadmium	0.35	Magnesium	20
Carbon	100 - 170	Nickel	65
Chromium	67	Nitrogen	100
Copper	50	Silicon	100
(U ²³⁵) 3.50 ± 0.005%			

TABLE III

TYPICAL MELT AND CAST CYCLE FOR FORTY-FOUR 0.603-IN. DIAMETER BY 13-1/2-IN. LONG U-Mo RODS*

Time	Remarks	Volts	Amperes	kw	pf	Vac (μ)	Melt Temperature (°C)	Mold Temperature (°F)
9:30	Outgas	225	110	25	+2	100	875	
10:20	Power off	230	112	25	+1	200		320
10:50	Power on	230	111	25	+1	150		
11:20	Melting	235	108	25	+1	200	1125	720
11:40	Molten	245	106	25	+1	175	1180	840
11:55	Calm	245	106	25	+1	150	1250	960
12:25	Cut power	240	102	23	+1	140	1330	1170
12:50	Raise power	245	105	24	+2	125	1380	1490
1:15	Pour	240	102	23	+1	125	1405	1525
1:18	Cut power							
1:50	Add helium							

*Charge: 44,356 g 3.45% uranium derby
716 g remelt
4,928 g molybdenum pellets
148 g molybdenum pellets excess

E. MACHINING OF CASTINGS

Several methods were used and evaluated for cutting slugs to specified lengths. The conventional procedure for cutting of the cast slug to approximate length on a hydraulic saw and then machining to length on the lathe, proved too costly. In addition, metal losses with the above procedure were considered too high, particularly since enriched uranium was used. However, a satisfactory process for cutting castings to finished length tolerances was achieved with abrasive cutting techniques. An aluminum-oxide, rubber-bonded, abrasive wheel was found to perform satisfactorily for cutting rods to specified tolerances.

F. METALLURGICAL EVALUATION

In the following discussion, the properties which can be controlled during the casting of U-Mo slugs are considered.

1. Density

Density measurements have been determined for two 0.590-in. diam by 13.125-in. long U - 10 Mo slugs. The volumetric method was employed and all necessary correction factors were applied to obtain an apparent density within ± 0.05 g/cc. The pins were allowed to soak approximately 16 hr in 150-Octanol to insure complete wetting.

The final apparent density was calculated from the formula:

$$d_{mt} = \frac{W_a \cdot d_{et}}{W_a - W_e}$$

where:

d_{mt} = Density at $t^{\circ}\text{C}$

W_a = Weight in air

d_{et} = Density of liquid at $t^{\circ}\text{C}$

W_e = Weight in liquid

The following data was obtained:

Slug No.	Dry Wt (g)	Wet Wt (g)	Temperature (°C)	Liquid Density (g/cc)	Reported Density (g/cc)
1	1023.642	974.139	22.7	0.8254	17.13
4	1018.522	969.160	22.5	0.8285	17.10

Similarly, for the production phase it was considered representative to take 20 g wafers from both ends of three as-cast rods to determine density for each heat. Results obtained are tabulated in Table III.

2. Homogeneity

Normal segregation is defined as the variation of the minor constituent from the surface to the core of the casting. This was the segregation pattern of the slugs cast in the heated mold. The U-Mo alloy, from indicated results, was essentially a binary alloy held to 10.00 ± 0.5 wt % molybdenum.

Several methods for the determination of molybdenum in uranium were investigated and the most reliable procedure appeared to be the X-ray spectrographic method. This is described as follows:

The Norelco X-ray Spectrograph was operated at 50 kw and 40 ma of current. A lithium fluoride analyzing crystal was used to disperse the X-ray spectra and a scintillation counter was used to detect the intensity of the spectrum lines. The intensity of the ka line of silver and the kb line of molybdenum was measured. The ratio of the intensity of molybdenum to the intensity of silver of standard samples was plotted against the percent to establish the working curve for the determination of the amount of molybdenum in the uranium samples. Reliability of obtained results were considered good in relation to density measurements and weight percent of molybdenum added per charge.

3. Chemical Composition

Interaction of carbon was prevented with sodium silicate-magnesium zirconate barrier on graphite components (approximately 8 mils thick).

Figure 6a. Bottom Transverse Microstructure of
U - 10 Wt % Mo As-cast Rod 100X

Figure 6b. Center Transverse Microstructure of
U - 10 Wt % Mo As-cast Rod 100X

Figure 6c. Top Transverse Microstructure of
U - 10 Wt % Mo As-cast Rod 100X

Composite charges of 50 wt % virgin and 50 wt % remelt scrap were considered the upper limit for good carbon control. In addition, a molten period of 120 min was established as maximum to prevent excess carbon pickup.

4. Microstructure

Several 12-in. long castings were cut into three 4-in. long pieces to determine grain size variations of each cast slug. Typical transverse microstructures of each section from one casting are shown in Figure 6. The structure is characterized by fine discrete dispersed particles of carbide. Grain sizes for different transverse sections show a No. 5 ASTM size for the lower end, to a No. 4 at the center, to a No. 3 ASTM size at the top. Since as-cast materials were requested, no heat treatment was performed to obtain a more uniform grain size.

5. Soundness

Various radiography sources, such as cesium-137, 3-1/2 c intensity, X-ray, 250 kv, and cobalt-60, 5 c intensity, were tried to determine their effectiveness in penetrating U-Mo cast slugs. Only gamma-ray radiography was found to detect voids in the order of ten mil thickness in a reasonable amount of time (approximately 8 min). Other sources were much too slow and poor resolution of details were noted. Typical internal structures of as-cast rods are shown in Figure 7. Note the clear definition of centerline porosity in the defective casting (No. 4).

6. Hardness

As-cast U - 10 wt % Mo rods indicated a hardness range of 276 to 288 DPH on the transverse sections.

7. Surface

Moderate temperature differences in the ATJ heated mold produced the desired progressive solidification to insure the surfaces of as-cast materials free of cold shuts, laps, scabs, gouges, and folds. A surface comparator indicated finishes in the range of 120 to 60 rms for materials cast in ATJ graphite and ranges of 800 to 600 rms in CS and CMD graphite grades.

Figure 7. Typical Radiograph of 0.590-In. Diam U - 10 Wt % Mo Cast Rods

8. Dimensional Controls

Experimental casting results showed that $0.603 \pm 0.000 - 0.003$ -in. diam holes in graphite with approximately 2-mil thicknesses of magnesium zirconate wash were necessary to insure 0.590 ± 0.005 -in. diam cast rods. Concentricity of each hole had to be ± 0.005 -in. in 14-in. mold length to obtain warpage tolerances, i.e., 0.005-in. maximum for single throw. Standard abrasive wheel cutting techniques were used to produce 12.000 ± 0.010 -in. lengths required.

Figure 8. Typical Wrought Method For Slug Fabrication

III. PRODUCTION OF URANIUM ALLOY AS-CAST U-MO PINS

Fabrication processes such as hot rolling or extrusion with either machining or cold working to size could be considered for making U - 10 Mo slugs (Figure 8). However, favorable experimental data for multiple casting of identical shapes in graphite resulted in the development of a more economical method.

Figure 9. Process Flowsheet for 0.590 $\pm$ 0.005-in. by 12-in. Long U-Mo Pin

The production of U-Mo alloyed slugs involved the converting of uranium derby material, scrap, and molybdenum metals to molten metal of satisfactory chemical composition and metallurgical quality for casting into multiple cavity molds. Semi-finished castings were then cropped, sampled, cut to length, deburred, stamped for heat identity, and inspected. Figure 9 is representative of AI's process for slug fabrication. Note a minimum of processing in comparison with the wrought process. The production operations are described in the following sections.

A. PREPARATION OF MELT CHARGE

Approximately 3450 kg of enriched uranium derby metal was prepared for optimum size for melting in a bottom-stoppered graphite crucible by cutting initial 140 kg uranium lots into 40 kg pieces. The metal loss incurred for this charge preparation was approximately 1%. This unremeltable material which is only suitable for chemical reprocessing, could be minimized by using knock-out pour-plug techniques, rather than the center stoppered lift-pour rod method.

B. MELTING

Melting equipment and practices were influenced by several inherent characteristics of uranium; its high density, fairly high melting temperature, activity in air, pyrophoricity, and radiation hazards.

1. Equipment

A 50 kw, 3000-cycle, induction furnace was used for melting U-Mo alloy. The furnace assembly, graphite crucible, and mold, were housed in a horizontal chamber with removable top and bottom sections. The chamber was 42-in. in diam, made of 3/8-in. thick stainless steel and water cooled. Satisfactory vacua in the leak tight chamber were obtained with a 280 cfm capacity vacuum pump. Helium gas was used primarily to purge furnace prior to crucible and mold discharge. Finally, melt area was maintained at a negative pressure to insure maximum number of changes.

2. Melting Procedure

The major operations carried out in the melting were charging, melting, and alloying. A batch system consisting of a predetermined weight of uranium derby, scrap, and molybdenum pellet randomly distributed in graphite crucible, was used for melt stock. It was required to make up 96 such batches to produce necessary castings. Weight adjustments for each heat were accomplished with molybdenum and remelt additions rather than virgin enriched uranium.

A rate of 2 heats per 16-hr day was maintained using the cycle as shown in Table III. Approximately 12 graphite crucibles were required for the 96 heats produced. The actual melt loss for melting was in the order of 3.0 to 4.0%. This was recovered in crucible skulls which were returned to chemical reprocessing.

C. CASTING

A total of 96 unit castings were necessary to produce sufficient material for 3900 ft of U-Mo rods. The average life of a 44-cavity ATJ mold was ten castings and for the 90-cavity mold an average of five. The slug casting yield for process was approximately 87.0%.

D. FUEL ROD PREPARATION

Since all rods were cast to the 0.590 ± 0.005 -in. diam required, no surface conditioning was necessary. Only 12 aluminum-oxide rubber bonded abrasive wheels were needed to cut 3900 U-Mo castings to size. The average metal loss as sawdust was 3.5 g per individual cut. A finished casting yield of about 78 to 80% was achieved during the production phase.

E. QUALITY CONTROL

1. Chemistry Composition

Approximately 600 samples (about 10 g per specimen) were submitted for carbon and molybdenum analyses and about six hundred 15 g wafer specimens for density measurements. Results, as indicated in Table IV, showed that the following chemical compositions were maintained:

Carbon (ppm)	800 maximum
Molybdenum (wt %)	10.00 ± 0.50
Density (g/cc)	17.00 to 17.25 range, as-cast

2. Physical Evaluation

Fabricated pins were 100% inspected for diameter, warpage, and length tolerances. As-cast rods were visually inspected for gross surface defects only. Approximately 10% of the rods were radiographed for apparent soundness. All slugs were stamped for heat identification and number per casting. The inspected slug to good slug yield was 94% (4110 inspected to 3856 accepted).

F. METAL YIELD

Representative metal yields and losses are indicated as follows:

	<u>%</u>
Metal yield	92.9
Slug casting yield	88.0
Finished casting yield	80
Metal skull loss	3.1
Cutomatic sawdust	<u>4.0</u>
Total	7.1

TABLE IV
MASTER CONTROL FOR INDIVIDUAL U - 10 WT % Mo CASTING HEATS

Heat No.	Charge No.	Molten Time (min)	Pour Temperature (°C)	Mold Temperature (°F)	Helium Cool (min)	Vacuum at Pour (μ)	Vacuum After Pour (μ)	Mold Drying (days)	Weight Mo Added (%)	Chemical Analysis C (ppm)	Chemical Composition Mo (%)	Density (g/cc)	Visual Appearance	Porosity (γ)	Type Graphite	Dimensions	Slug Yield	Remarks
688	1*	100	1390	1300	30	200	200		10			17.10-17.18	Good		ATJ	Good	44-44	
690	1	90	No Reading	930	30	160	160		10			17.17-17.19	Good			Oversize	44-41	
691	1	100	1400	1100	30	350	350		10			17.16-17.00	Good	Fair			44-42	
692	1	90	No Reading	1000	30	150	200		10				Fair	Fair			25-15	
693	1	90	1405	No Reading	30	200	200		10			17.07-17.09	Fair	Fair			44-39	
694	1	65	No Reading	1100	30	140	140		10			17.07-17.09	Fair	Fair			38-28	
695	1	95	1435	1140	30	125	125		10			17.19-17.20	Fair	Fair			44-12	
696	1	65	1375	1060	30	70	81		10			17.00-17.08	Fair	Good			37-24	
697	1	110	1420	No Reading	30	190	190		10			17.00-17.16	Good				37-20	
698	1	90	1410	1160	30	150	150		10			17.03-17.16	Good	Good		Good	44-44	
699	1	80	1400	1060	10	260	270		10			17.00-17.11	Good	Good		Good	44-44	
724	1	95	1408	No Reading	30	175	175	12	9.9	540-590	9.7-9.8	17.00-17.10	Good	Good		Good	43-43	
725	1	90	1415	No Reading	32	200	200		10				Rough Bad	Bad	CS	Bad	90-38	
727	1	95	1405	No Reading	30	150	150	1	9.8		9.9-9.8	17.14-17.20	Good		ATJ	Good	44-44	
728	1	100	1412	1300		185	185	2	9.9	500-660	10.5-10.2		Good	Erosion Marks			44-44	Cut 6 in.
729	1	94	1400	1200	27	175	200	3/4	10.1	350-480		17.14-17.04	Good	Fair			44-44	
730	1	94	1406	1100	30	173	173		10			17.12-17.20	Good	Fair			44-44	
731	2†	105	1405	1140	25	130	130	1	10	430-560		17.15-17.20	Good	Good			43-43	
732	1	95	1410			125	125	3/4	10	480-560		17.24-17.25	Good				44-44	
733	1	95	1403		27	100	125	3/4	10			17.16-17.19	Good				44-44	
734	2	90	1407	1300		105	105	3/4	10	380-520	10.1-9.6		Good				43-40	
735	2	100	1410	1595	28	200	200	3/4	10	420-580	10.4-10.3	17.22-17.23	Good				43-43	
736	2	100	1430	1330		110	110	1 3/4	10.1	370-460	10.0-10.2	17.10-17.20	Good				44-44	
737	1	95	1405	1320	28	115	115	1 3/4	10	370-460	10.3-10.2	17.15-17.25	Good				40-40	
738	1	90	1410	1220	30	100	100	2	10	470-340		17.20-17.30	Good				44-40	
741	2	90	1408	1230	28	130		2	10		9.7-9.6		Good				43-40	
742	2	80	1410	1260	30	115	115	3/4	10	450-500	9.9-9.8		Good				40-37	
744	1	90	1405	1120	29	150	150	1	10	900-1100	10.3-10.1		Good				39-38	
745	1	95	1410	1240	28	200	200	3/4	10	420-500	10.1-9.8		Good				38-35	
746	2	85	1405	1060	28	88	130		10	920-990		16.90-17.08	Cracks Bad	Bad		Oversize	Rej	
747	1	100	1410	1245	32	190	200	9	10	490-520	10.0-9.8		Good			Oversize	39-32	
748	2	95	1408	1240	28	144	144	3/4	10		9.9-9.8		Good			Oversize	44-44	
749	1	90	1410	1280	29	200	200	7	10	800-910		16.90-17.00	Rough Bad	Bad	CS	Oversize	Rej	

TABLE IV (Continued)

MASTER CONTROL FOR INDIVIDUAL U - 10 WT % Mo CASTING HEATS

Heat No.	Charge No.	Molten Time (min)	Pour Temperature (°C)	Mold Temperature (°F)	Helium Cool (min)	Vacuum at Pour (μ)	Vacuum After Pour (μ)	Mold Drying (days)	Weight Mo Added (%)	Chemical Analysis C (ppm)	Chemical Composition Mo (%)	Density (g/cc)	Visual Appearance	Porosity (γ)	Type Graphite	Dimensions	Slug Yield	Remarks
753	2	110	1408	1435	36	150	150	2	10	420-560			Good		ATJ	Good	44-44	
755	2	102	1410	1420	28	150	150	1	10	310-310	10.3-10.0	17.19-17.15	Good		ATJ	Good	36-36	
757	2	90	1405	1350	31	140	140	1	10.0	660-720	10.4-10.3	17.14-17.14	Rough	Bad	CS	Bad	90-23	
759	2	95	1410	1440	29	150	150	2	10.0	500-520	9.6-9.6	17.25-17.23	Good		ATJ	Good	44-44	
760	2	95	1405	1515	36	140	140	2-1/2	10.0			17.17-17.16	Good			Good	44-44	
761	2	95	1405	1420	28	150	150	1	10.0	750-790	10.1-10.4		Good			Good	44-44	
763	2	95	1410	1485	29	125	125	1	10.0	420-650	10.1-10.4	17.18-17.20	Good			Good	44-44	
764	2	90	1405	1380	28	125	125	1	10.0	730-760		17.14-17.14	Good			Good	44-44	
765	2	90	1405	1490	34	110	110	3/4	10.0			17.18-17.18	Good			Good	44-44	
766	2	100	1405	1240	29	190	190	1	10.0	560-590		17.07-17.14	Good			Good	44-44	
769	2	90	1410	1505	33	90	125	3/4	10.0			17.12-17.16	Good			Good	41-41	
771	2	100	1405	1250	31	100	100	1-3/4	10.0			17.00-17.10	Good			Good	44-44	
774	2	100	1412	No Reading	28	140	140	1/3	10.0			17.12-17.18	Good			Good	41-41	
775	1	90	1405	1220	28	180	180	2	10.0				Good			Good	44-44	
777	2	90	1405	1525	34	125	125	1/3	10.0			17.05-17.05	Good			Good	44-44	
778	2	90	1410	1400	28	125	125	1/2	10.2	680-770		17.12-17.13	Fair	Fair	872TS	Good	90-90	
780	2	90	1405	1615	29	110	160	1	10.4			17.06-17.08	Good		ATJ	Good	44-44	
781	2	75	1405	1380	29	90	90	1/4	10.4	400-450	10.4		Fair		872TS	Good	90-90	
783	2	94	1405	1580	27	90	90	1-1/2	10.2	500-560	10.4-10.3		Good		ATJ	Good	44-44	
784	2	82	1405	1260	60	150	150	1/4	10.1				Fair	Fair	872TS	Good	89-89	
786	2	105	1405	1680	29	160	125	3	10.3				Fair	Good	ATJ	Good	41-41	
787	1	75	1405	1400	30	200	200	1/4	10.4	740-790	10.0-10.2		Good		872TS	Good	83-83	
788	2	Dud	Dud						10.2				Dud		ATJ		Dud	
789	2	90	1410	1355	27	170	180	2	10.1			17.05-17.06	Good	Good	ATJ	Good	44-44	
790	2	75	1405	1200	28	190	190	1-1/2	10.1				Fair	Bad	872TS	Good	83-83	
791	2	120	1415	1160	28	120	140	2	10.1				Good		ATJ	Good	44-44	6-in. Long
792	2	85	1405	1570	34	200	200	2	10.3			17.07-17.07	Good		ATJ	Good	41-41	
793	1	85	1410	1240	28	200	200	1/4	10.1	440-480	10.4-10.4		Fair		872TS	Good	80-80	
794	2	90	1410	No Reading	29	150	150	1/4	10.3						872TS		Dud	
795	2	90	1405	No Reading	30	200	200	2	10.3	510-500		17.12-17.10	Good		ATJ	Good	41-41	
796	2	95	1410	1450	32	140	140	3/4	10.3	410-640		17.12-17.16	Fair		872TS	Good	50-50	
797	2	90	1410	1420	29	150	150	1-1/2	10.2	320-440	10.3-10.2		Good		ATJ	Good	41-41	
798	1	90	1410	1545	29	150	150	1-1/2	10.01	420-410	10.2-10.1	17.23-17.25	Good			Good	41-41	
799	2	85	1405	1220	27	180	180	3/4	10.3	460-488	9.7-9.8		Good			Good	44-44	
800	2	100	1410	1420	29	160	160	3/4	10.2	360-500	10.6-10.2		Good			Good	42-42	

TABLE IV (Continued)

MASTER CONTROL FOR INDIVIDUAL U - 10 WT % Mo CASTING HEATS

Heat No.	Charge No.	Molten Time (min)	Pour Temperature (°C)	Mold Temperature (°F)	Helium Cool (min)	Vacuum at Pour (μ)	Vacuum After Pour (μ)	Mold Drying (days)	Weight Mo Added (%)	Chemical Analysis C (ppm)	Chemical Composition Mo (%)	Density (g/cc)	Visual Appearance	Porosity (γ)	Type Graphite	Dimensions	Slug Yield	Remarks
801	2	90	1405	1400	30	150	150	3/4	10.3	390-570	10.3-10.5		Good		ATJ	Good	42-41	
802	2	85	1405	1560	29	130	130	3/4	10.3	430-500	10.5-10.1		Good			Good	44-44	
803	1	100	1405	1510	29	110	110	2	10.2	640-660	10.6-10.3		Good			Good	43-38	
804	2	105	1410	1450	29	125	125	2	10.1	600-620	10.4-10.6		Good			Good	40-40	
805	2	110	1410	1540	29	105	105	3/4	10.2	700-690	10.2-10.0		Good			Good	44-44	
806	2	105	1410	1480	29	125	125	3/4	10.2	540-560	10.1-10.4		Bad			Bad	41-19	
807	Remelt	105	1400	1525	29	130	130	3/4	10.2	760-840	10.3		Good			Good	44-44	
808	Remelt	105	1410	1460	29	150	150	3/4	10.2	620-710	10.4-10.1		Good			Good	44-44	
809	Remelt	105	1410	1540	29	150	150	3/4	10.2	540-610	10.0-10.4	17.05-17.05	Good			Good	44-44	
810	Remelt	105	1410	1460	29	150	150	3/4	10.2	850-660	10.1-9.8		Good			Good	40-40	
811	2	105	1405	1545	29	150	160	3/4	10.2	470-460	10.2-9.8		Good			Good	44-44	
812	2	105	1405	1600	29	130	130	3/4	10.2	320-320	10		Good			Good	41-41	
813	2	105	1410	1400	29	150	150	2	10.2	610-570	10.0-9.9		Good			Good	33-32	
814	2	105	1405	1505	29	150	160	2	10.4	340-340	10.4-10.4	17.10-17.16	Good			Good	43-43	
815	2	105	1405	1500	No Reading	170	170	2	10.2	530-470		17.10-17.20	Good			Good	44-44	
816	2	105	1410	1450	59	190	190	1	10.2	730-720	10.0-10.1		Erosion Marks			Fair	44-40	
817	2	105	1410	1590	34	150	150	1 1/4	10.2	550-540	9.8-10.1		Good			Good	40-40	
818	Remelt	105	1410		No Reading	190	190		10.2	810-810		17.08-17.08	Erosion Marks			Fair	40-21	
819	2	100	1405	1550	29	80	90	3/4	10.8	900-860	10.0-10.1		Good			Good	44-44	
820	2	100	1410	1440	29	110	110	1/4	10.4	600-590	9.7		Erosion Marks			Fair	40-30	
821	2	105	1405	1575	29	125	125	1	10.4	700-690	10.0-9.7	17.12-17.12	Good			Good	39-39	
822	2	100	1410	1440	29	150	150	1	10.3	520-490	10.4	17.17-17.17	Good			Good	44-40	
823	2	80	1410	1400	29	150	150	2	8-9	530-500	7.98-8.08	17.40*	Low Chemical					Reject
824	2	120	1410	1000	No Reading	150	150	2	10.2	560-510		17.18-17.18	Erosion Marks			Good	44-29	
825	Remelt	100	1405	1220	34	130	150	2	10.2	650-620	9.9-9.9	17.11-17.11	Good			Good	39-38	
826	Remelt	115	1405	1280	28	85	85	3/4	10.2	770-680	10.1-9.9	17.12-17.12	Good			Good	43-43	
827	Remelt	100	1405	1350	No Reading	80	80	3/4	10.2	570-560	10.1-10.2		Good			Good	41-41	
828	Remelt	110	1405	1000	36	100	100	3	10.2	740-680	10.4-10.5	16.90-17.15	Good			Good	42-42	

*No. 1 = Virgin Charge

†No. 2 = Composite Charge

It is interesting to note that a 7.1% nonremeltable scrap was accumulated from the processing of 3450 kg of slightly enriched uranium. Approximately 50% of this scrap was in U-Mo alloyed materials. A typical process yield for a 44-unit mold is shown in Figure 10.

* All weight figures in grams

Figure 10. Representative Metal Yield for Pin Fabricating Per 44-Cavity Mold

IV. CONCLUSIONS

The casting of U - 10 Mo alloys into slugs of approximately 0.6-in. in diam, 12-in. long, using a multicavity mold, is feasible.

The homogeneity, surfaces, and dimensional tolerances of the as-cast slugs met all requirements for nuclear fuel materials.

It appears that the casting method for producing slugs is economical, due to the good yield of finished slugs from virgin material.

The graphite used for molds and crucibles, as well as the melting cycle, is an important variable in the process.