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MASTER

CONSUMABLE-ELECTRODE ARC MELTING
OF URANIUM

BY

R. L. SCHARDT

AEC RESEARCH AND DEVELOPMENT REPORT

RELEASED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

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CONSUMABLE-ELECTRODE ARC MELTING OF URANIUM H.C. \$3.00; MN-65

By

R. L. Schardt

of

RELEASED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

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ABSTRACT

A consumable-electrode arc-melting test was performed at the Nuclear Metals Division of the National Lead Company, Albany, New York. The electrodes for arc-melting were produced by vacuum-induction-melting uranium feedstock and casting it into 5½-inch-, 8-inch-, and 9-inch-diameter molds. These electrodes were arc-melted in a vacuum into 7-, 7⅝-, 10-, and 11-inch-diameter (production-size) ingots.

Procedures for the arc-melting of uranium were established, and the effects of the process on the residual impurity levels in the uranium ingots were determined. Metallographic studies showed that the inclusions were finely divided and evenly distributed. Chemical analyses indicated that no chemical refinement, except for a small reduction in hydrogen content, could be attributed to the arc-melting process.

Limited cladding and reactor tests indicated that fuel cores fabricated from arc-melted uranium performed as well as cores from regular induction-melted stock.

1. INTRODUCTION

Concern by the reactor sites with the variation in reactor performance from ingot to ingot generated interest in consumable-electrode arc melting as a possible means of improving uranium ingot consistency. The reactor sites also expressed concern about the segregation of chemical contaminants and the size and the distribution of the carbide particles found within each induction-melted ingot. Previous, small-scale tests^{1,2,3} made under the supervision of the National Lead Company of Ohio showed a substantial improvement in chemical homogeneity, control of carbide size, and carbide distribution through consumable-electrode arc melting of induction-melted uranium feedstock. These tests also indicated that excellent fuel-core-to-good-fuel-core yields were obtainable through the arc-melting route.

To test the process on a larger scale, a contract was made with the National Lead Company, Nuclear Metals Division, Albany, New York, to arc-melt induction-melted uranium electrodes into ingots of various sizes.

2. OBJECTIVES

The purpose of this test was three-fold:

1. To determine the feasibility of casting production-size uranium ingots by vacuum arc-melting and, if feasible, to establish casting parameters.
2. To determine the effect of consumable arc-melting on the quantity and distribution of chemical impurities in ingots.
3. To evaluate the metal quality of NPR, Mark VB, and I & E fuel cores produced from the arc-melted ingots and to provide fuel cores for reactor performance tests.

3. SUMMARY OF RESULTS

Forty-two production-size ingots were made in this test of consumable-electrode arc-melting. The quantities and types of ingots produced are listed in Table I.

TABLE I Summary of Consumable Arc-Melted Ingots

Test Phase	Number of Ingots	Nominal Diameter (in.)	Nominal Length (in.)	Isotopic Enrichment	Est. Ingot Weight (lb)	Core Type
I	11	11	22	0.94% U ²³⁵	1430	NPR
II	6	11	22	Normal	1430	I & E
III	5	10	25	Normal	1340	VB
IV	10	7 ³ / ₈	22	Normal	640	VB
V	10	7	25	Normal	660	I & E

3.1 Process Feasibility and Parameters

Arc-melting was demonstrated to be feasible for making production-sized uranium ingots. The parameters established to accomplish melting under the conditions of the test were as follows:

Ingot Diameter (in.)	Voltage	Amperage	Power (kw)
7 and 7 ³ / ₈	25	5600	140.0
10	25	8000	200.0
11	26	9900	257.4

3.2 Metallographic and Chemical Analyses

A metallographic examination (at 100X) of etched ingot sections showed that the ingots contained a fine, evenly dispersed pattern of carbides and other nonmetallic inclusions. An examination of vertical ingot sections revealed primary pipe, centerline voids, rimming, and other scattered voids ¹/₁₆ inch or less in diameter.

Samples were taken from the top and bottom of the electrodes (feedstock for arc melting) and from corresponding positions in the arc-melted ingots for chemical analysis. A "within-ingot" study of the distribution of chemical impurities was also made. Both investigations indicated that there were no significant changes in the chemical composition of the uranium after arc melting, except for a small reduction in the hydrogen content and a slight segregation of oxygen, nitrogen, and carbon in some ingots.

3.3 Metal Quality and Reactor Performance

NPR billets and 7-inch HAPO I & E fuel cores fabricated from the arc-melted ingots had a higher-than-usual rejection rate, probably because of the surface and subsurface voids formed during solidification. This high rejection rate did not occur in the VB fuel cores fabricated from the 10-inch-diameter ingots which were machined to 9 inches in diameter prior to extrusion.

Fuel cores fabricated from arc-melted ingots were canned and subjected to a reactor test at Savannah River. Their performance was considered equivalent to fuel cores from standard, induction-melted ingots. Billets extruded from arc-melted ingots were shipped to Hanford where they were coextruded. The billets clad satisfactorily with an average cladding variation of less than 5 mils.

4. EQUIPMENT

The consumable-electrode arc-melting furnace used in this work (Figure 1) was manufactured by the Lectromelt Corporation, Pittsburgh, Pennsylvania. It was designed for melting refractory and reactive metals under vacuum or in controlled atmospheres. The furnace contains the following principal components:

1. An electrode drive assembly equipped with both automatic and manually controlled feed systems. The drive system, bus bars, and electrode stem were air-cooled.
2. A crucible assembly (Figure 2) consisting of a massive copper cylinder and base plates. (This mass of copper provided the only source of ingot cooling.)
3. A vacuum system consisting of a blower and a roughing pump.
4. Furnace instrumentation consisting of:
 - a. A thermocouple vacuum-sensing element located in the fore line between the furnace shell and the exhaust valve. The meter is located on the instrument panel (Figure 3).
 - b. Electrical meters (see Figure 3) consisting of a voltmeter, an ammeter, and a watt-hour meter.
 - c. A multipoint recorder attached to chromel-alumel thermocouples for recording the crucible temperatures.

The maximum current capacity of the furnace was 10,000 amperes. The maximum electrode size was 9 inches in diameter by 55 inches long. The furnace could produce uranium ingots as large as 11 inches in diameter by 27 inches long.

FIGURE 1 Lectromelt Consumable-Electrode Arc-Melting Furnace

1262-8

FIGURE 2 Copper Crucible for 7-Inch-Diameter Ingot with Copper Base Plate and Uranium Starting Pad

FIGURE 3 Instrument Panel

5. PROCEDURES

5.1 Electrode Preparation

Electrodes of three sizes were produced by vacuum-induction melting uranium feedstock in uncoated crucibles and casting into MgO wash-coated molds. A summary of the conditions used in preparing the electrodes appears in Table II.

The induction furnace operating conditions were as follows:

- 5.1.1. The furnace starting pressure was maintained at 50 microns or less with a leak rate of less than 20 microns per minute.
- 5.1.2. The melting cycle was 165 kw to the melting point, 100 kw to approximately 2450 °F, and pour.

All of the electrodes (see Figure 4) were grit-blasted with MgF_2 slag to remove surface oxidation and were machined to provide a groove for attaching the electrode holder.

TABLE II Consumable Arc -Melting Electrode Requirements

Test Phase	Electrode Diameter (in.)	Finished Length (in.)	Feedstock for Electrode	Feedstock Weight (lb)
I	9	40	Three Derbies, Solid Scrap, Briquettes (15% max)	2025
II	9	40	Three Derbies, Solid Scrap, Briquettes (25% max)	2025
III	8	46	Three Derbies, Solid Scrap	1800
IV	5.5	48	One Derby, Solid Scrap	900
V	5.5	48	One Derby, Solid Scrap, Briquettes (25% max)	900

1214-3

FIGURE 4 Typical Grit-Blasted Electrodes

5.2 Arc-Melting

The arc melting was performed in the Lectromelt furnace using the following procedure:

- 5.2.1. A 1-inch-thick uranium pad (see Figures 2 and 5), previously cast and machined at the National Lead Company of Ohio, was placed in the bottom of the crucible.
- 5.2.2. Approximately 1 pound of chips or small pieces of uranium was placed on top of the uranium pad. This metal was used as starting material to strike the arc.
- 5.2.3. The electrode was placed in the furnace and attached to the drive assembly. The furnace was evacuated to a pressure of less than 40 microns before melting was started.
- 5.2.4. The electrode, which was the cathode throughout the test, was lowered to strike the arc, and melting proceeded. It was thought that the negative polarity of the electrode would result in a shallow molten pool which would freeze rapidly, thus allowing less time for liquation of the insoluble nonmetallic inclusions to occur.
- 5.2.5. Amperage, voltage, pressure, and crucible temperature readings were recorded during the melt. Pressure measurements were taken with a thermocouple gage located in the furnace

FIGURE 5 Uranium Starting Pad (10 Inches in Diameter)

foreline between the furnace shell and the exhaust valve; therefore, the pressures recorded do not necessarily reflect the pressure directly over the melt. In all cases, however, the pressures rose rapidly when the arc was struck and soon reached a maximum value. The pressures remained near this maximum value until the arc was extinguished. Thermocouple readings were taken at three locations in the wall of the crucible. Temperature measurements were made on only five heats since the readings were consistent from heat to heat.

- 5.2.6. The arc was controlled by a servomechanism which, by raising or lowering the electrode, balanced the arc voltage against a preset reference voltage. The current used could be varied from 0 to 10,000 amperes. Table III lists the pertinent test conditions for each phase.
- 5.2.7. Near the completion of the melt, the power was reduced by a predetermined amount in 30-second increments until the arc was extinguished. This hot-topping procedure was adopted to reduce the formation of voids as the ingot solidified.

5.2.8. After melting was completed, the ingot was cooled to 750°F in the furnace under one-half atmosphere of argon before removal. An as-cast ingot is shown in Figure 6.

TABLE III Arc-Melting Conditions

Test Phase	I	II	III	IV	V
Weight Copper Crucible (lb)	3960	3960	4159	1736	2060
Crucible Dimensions (in.):					
ID	11.300	11.300	10.250	7.650	7.187
OD	24.5	24.5	24.5	17	17
Height	34.25	34.25	34.5	29	32
Furnace Pressure, Operating Range (μ)*	16 to 65	27 to 90	15 to 170	14 to 42	10 to 250
Current (ka)	9.8 to 10.0	9.8 to 10.0	7.9 to 8.1	5.5 to 5.7	5.5 to 5.7
Voltage	25 to 27	25 to 27	24 to 26	24 to 26	24 to 26
Melting Rate (lb/hr)	2641	2831	2244	1536	1587
Ingot Weight (lb)	1599	1425	1388	687	678

* Starting pressure was 40 microns or less.

NOTE: The maximum breakout temperature for all ingots was 750°F.

1262-9

FIGURE 6 Typical, Arc-Melted Ingot (7 Inches in Diameter by 25 Inches Long)

5.3 Control Ingots

An important part of this program was to compare the metallography of the arc-melted product with that of typical induction-melted ingots produced at the National Lead Company of Ohio. Therefore, induction-melted control ingots were cast from the same types of charge materials as were used to cast the arc-melted electrodes. Standard production procedures were employed in melting and casting.

The control ingots were cast and fabricated concurrently with the arc-melted material to eliminate any effects due to time.

6. DISCUSSION OF RESULTS

6.1 Furnace Performance

Reactor-grade ingots were produced by consumable-electrode arc melting. Particular attention was paid to the stability of the arc and to the evolution of volatiles during the melt. Occasionally, bubbling was visible on the pool surface accompanied by vigorous splattering from the electrode surface.

During all melts, regardless of ingot size, the phenomenon known as "glow-discharge" occurred approximately half way through the melting cycle. A glow-discharge is an arc which moves up the electrode and crucible from its intended position at the electrode tip. This displaced arc does not melt the electrode, but does heat the crucible wall rapidly. Glow-discharge is apparently caused by a combination of electrical and positional instability of the two electrodes. Observations made by Johnson, Hahn, and Itoh⁴ indicated that (1) at pressures down to 30 torr, the anode is positionally stable, (2) at pressures below 30 torr, the anode becomes positionally unstable, and (3) at approximately 0.4 torr, the cathode becomes stably affixed to the electrode tip, thus restoring the arc stability.

The periods of "glow" became more frequent and lasted longer as the melt progressed. During the longer periods of "glow," the metal could be seen to solidify radially from the walls of the crucible.

Generally, the arc remained hard and stable except during the periods of "glow" and during the hot-topping period. However, if the reference voltage was set too high, a long arc resulted with excessive arcing to the side wall and excessive side wall splatter. On the other hand, if the reference voltage was set too low, the electrode would run down into the pool shorting the system. An examination of the crucible after use showed that the unstable arc during hot topping etched the crucible wall. This etching had no deleterious effect other than producing a rougher ingot surface on the succeeding melt.

The use of massive copper crucibles without the aid of external cooling media, such as fins, water, etc., is thought to be unique with this furnace installation. The crucibles proved satis-

factory for the smaller diameter ingots, i.e., 7, 7 $\frac{3}{8}$ and 10 inches. However, the massive copper crucible was not adequate for the larger, 11-inch-diameter, ingots. In many of the 11-inch melts, the copper crucible became overheated and alloyed with the uranium ingot at the interface. This bond made it almost impossible to separate the ingot from the mold.

A difficulty that occurred with crucibles of all sizes was growth of the copper from thermocycling. The inner diameter of the crucibles decreased with each succeeding melt. This growth made it necessary to rebore the crucibles after every fifth melt.

6.2 Chemical Analyses

6.2.1 Sampling Plan

Samples removed from the top and bottom of each electrode (feedstock) were analyzed for chemical composition prior to arc melting. After arc melting, samples from the top and bottom of each ingot were analyzed. Several arc-melted ingots from each test phase were selected for destructive testing; i.e., a chemical wafer was removed at 4- to 6-inch intervals along the ingot length (see Figure 7). All specimens (from both electrodes and ingots) were analyzed for carbon, nitrogen, hydrogen, oxygen, silicon, iron and density. Spectrochemical analyses were also run for aluminum, copper, magnesium, manganese, chromium, and nickel.

6.2.2 Results

A statistical investigation based on analyses-of-variance techniques using 95% confidence limits was used to determine the amount and distribution of the 12 elemental impurities listed in the preceding paragraph.

This investigation was conducted in two phases. The first was concerned with the comparison between the induction-melted electrodes and the arc-melted ingots produced from these electrodes. The results derived from this comparison indicated that there were no significant changes, except for hydrogen, in the chemical compositions for any size ingot. The average hydrogen levels were slightly lower in the ingots than in the electrodes. The differences may be seen in Table IV.

TABLE IV Reduction in Hydrogen Levels Between Electrodes and Arc-Melted Ingots (With 95% Confidence Limits)

Phase I	11-inch Enriched	-0.6 $\pm$ 0.1 ppm H ₂
Phase II	11-inch Normal	-0.7 $\pm$ 0.1 ppm H ₂
Phase III	10-inch Normal	-0.4 $\pm$ 0.1 ppm H ₂
Phase IV	7 $\frac{3}{8}$ -inch Normal	-0.3 $\pm$ 0.1 ppm H ₂
Phase V	7-inch Normal	-0.2 $\pm$ 0.1 ppm H ₂

FIGURE 7 Sampling Plan of Vertically Sectioned Ingots: (A) Scrap, (B) Chemical Sample, (C) Metallographic Samples, (D) Samples for Inclusion Count and Photomicrographs.

These reductions are statistically significant at the over-all hydrogen level of less than 2 ppm; however, they are no greater than would be expected for any process in which metal is double-melted in a vacuum.⁵

The second phase of this evaluation was concerned with the comparison of the chemical composition of the various levels within the vacuum arc-melted ingots produced. Again using the analyses-of-variance technique and 95% confidence limits, no statistically significant differences in chemical compositions were found within the ingots except for the following:

6.2.2.1 Oxygen (11-Inch-Diameter Ingots Only)

There were no differences noted between the edge and center portions of the ingots tested; however, there was a slight variation in the oxygen content from top to bottom of the ingots. This variation amounted to 5 ± 2 ppm. The pattern of oxygen distribution is shown in Figure 8.

6.2.2.2 Carbon (7-Inch-Diameter Ingots Only)

Again, there were no differences detected between the edge and center portions of the ingots tested; however, the 7-inch-diameter ingots contained carbon segregation extending from a level of 338 ± 15 ppm near the bottom of the ingots up to a level of 435 ± 15 ppm at the top. The pattern of carbon distribution is shown in Figure 9.

FIGURE 8 Oxygen Distribution in 11-Inch-Diameter Arc-Melted Ingots (Mean Values with 95% Confidence Limits)

FIGURE 9 Carbon Distribution in 7-Inch-Diameter Arc-Melted Ingots (Mean Values with 95% Confidence Limits)

FIGURE 10 Nitrogen Distribution in 7-Inch-Diameter Arc-Melted Ingots (Mean Values with 95% Confidence Limits)

6.2.2.3 Nitrogen (7-Inch-Diameter Ingots Only)

No differences were detected between the edge and center areas of the ingots tested; however, the 7-inch-diameter ingots exhibited nitrogen segregation amounting to 4 ± 3 ppm. The pattern of nitrogen distribution is shown in Figure 10.

In the opinion of the writer, the differences shown for the oxygen content, Figure 8, and nitrogen content, Figure 10, are, for practical purposes, negligible. Chemical analyses are given in Tables VI through XIV in the Appendix.

6.3 Metallography

6.3.1 As-Cast Specimens

The induction-melted and the arc-melted ingots were evaluated for inclusion content, and a comparison of the two types of ingots was made (see Figures 11 through 17).

In the arc-melted ingots, the carbides and other nonmetallic inclusions were small and fairly evenly distributed over the entire area of the as-cast samples. The carbide clusters were also small and were sparse.

In the induction-melted ingots, the carbides and other nonmetallics were relatively large. Some of the inclusions (see Figure 15) were elongated and tended to form a network-type structure. The clusters were also much larger and more numerous than those of the arc-melted ingots.

A peppery network was noted in the background of both types of ingots at higher magnifications. The inclusions in the induction-melted ingots were much larger and turned dark after a HNO_3 rinse, thus identifying this background material as uranium carbide. Several small hydrides were also found in each of the two types of ingots. These hydrides were smaller but more numerous in the arc-melted ingots.

Many of the nonmetallic compounds which are too stable to be chemically dissociated by the arc can be physically broken into smaller particles by the arc pressure. It is this type of action, in conjunction with the rapid freezing previously described, that is thought to be responsible for the size and dispersement of the inclusions found in the arc-melted ingots. A review of Figures 14 and 16 showed that the nonmetallic inclusions found in the 10- and 11-inch-diameter arc-melted ingots are larger than those found in the 7- and $7\frac{3}{8}$ -inch-diameter ingots shown in Figures 11 and 13. This increase in particle size is attributed to the slower cooling rate of the larger diameter ingots.

The metallographic evaluation of the arc-melted ingots revealed voids present in a rather scattered pattern. The major voids occurred along the centerline and as primary pipe; however, there were many smaller holes ($\frac{1}{16}$ -inch diameter or less) scattered throughout the ingots.

These voids are thought to be responsible for the high surface rejection rates of the NPR billets and the extremely high rejection rate of the 7-inch HAPO I & E fuel cores. This high rejection rate did not occur in the fuel cores processed from the 10-inch-diameter ingots which were machined* to 9-inches in diameter prior to extruding.

**The extrusion press at Reactive Metals, Inc., (formerly the Bridgeport Brass Company) did not have sufficient capacity to extrude the 10-inch-diameter billets into rods as originally planned; therefore, the billets were returned to this site for machining to 9 inches in diameter and then returned to RMI for extrusion.*

EDGE

MID-RADII

CENTER

NOTE: Photograph at left was taken actual size; photographs above were taken at 100X magnification; all were reduced 67% in reproduction.

FIGURE 11 Arc-Melted Ingot 7 Inches in Diameter

EDGE

MID-RADII

CENTER

NOTE: Photograph at left was taken actual size; photographs above were taken at 100X magnification; all were reduced 67% in reproduction.

FIGURE 12 Induction-Melted Ingot 7 Inches in Diameter

EDGE

MID-RADII

CENTER

NOTE: Photograph at left was taken actual size; photographs above were taken at 100X magnification; all were reduced 67% in reproduction.

FIGURE 13 Arc-Melted Ingot $1\frac{3}{8}$ Inches in Diameter

881 - (1 THRU 5)

881 - (21 THRU 23 & 54 THRU 65)

EDGE

MID-RADII

CENTER

NOTE: Photograph at left was taken actual size, photographs above were taken at 100X magnification; all were reduced 67% in reproduction.

FIGURE 14 Arc-Melted Ingot 10 Inches in Diameter

881 - (15 THRU 19)

881 - (33 THRU 47)

EDGE

MID - RADII

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FIGURE 15 Induction-Melted Ingot 10 Inches in Diameter

921-(158 THRU 163)

921-(215 THRU 224)

EDGE

MID-RADII

CENTER

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FIGURE 16 Arc-Melted Ingot 11 Inches in Diameter (0.94% Enriched)

921-(344 THRU 348)

921-(457 THRU 459; 475 THRU 483 & 490 THRU 492)

EDGE

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NOTE: Photograph at left was taken actual size; photographs above were taken at 100X magnification; all were reduced 67% in reproduction.

FIGURE 17 Induction-Melted Ingot 11 Inches in Diameter (0.94% Enriched)

6.3.2 Fabricated Specimens

Metallographic evaluations were made on samples removed from extruded NOE and NIE billets and from Hamford I & E rolled rods. Each sample was evaluated for inclusions, stringers, grain size, and recrystallization. The average results are summarized in Table V and discussed below. (The results of visual inspection of the fuel cores and billets produced are listed in Tables XV, XVI, and XVII.)

TABLE V Summary of Metallographic Results, Fabricated Rod and Billet Samples

Evaluation Category	Front of Billet (NPR) or Rod (I & E)						Rear of Billet (NPR) or Rod (I & E)					
	NPR	I & E	NPR	I & E	NPR	I & E	NPR	I & E	NPR	I & E	NPR	I & E
Inclusion Rating*	Concentration		Size		Type		Concentration		Size		Type	
Induction	1	11	E	B+	Random	Random	3	5	C+	D	Random	Random
Arc	11	11	A+	A+	Random	Random	11	11	A+	A+	Random	Random
Stringer Rating**	No. per Field		Average Length		Average Width		No. per Field		Average Length		Average Width	
Induction	—	2.5	—	1.8"	—	0.74"	—	3.5	—	2.3"	—	0.110"
Arc	—	1.7	—	1.0"	—	0.38"	—	0.5	—	0.3"	—	0.019"
Grain Size (mm)	OD		Mid Radii		Center		OD		Mid Radii		Center	
Induction	.027	.040	.004	.052	.031	.053	.023	.037	.023	.049	.013	.052
Arc	.025	.038	.003	.049	.013	.048	.021	.047	.004	.058	.015	.056
Recrystallization(%)	OD		Mid Radii		Center		OD		Mid Radii		Center	
Induction	48	85	0	85	20	70	30	100	20	100	10	100
Arc	40	100	0	65	0	65	30	100	0	90	10	85

* Inclusions are rated as follows:

Concentration — Average number of inclusions per ½ inch square at 100X.

Size — Ranges from A (fine) to E (very coarse).

** Length and width of stringers are given in inches at 100X.

NOTE: Readers wishing further information on the metallographic procedures and standards employed at this site are directed to Reference 6.

6.3.2.1 Inclusion Rating

The inclusions found in the rods and billets formed from both the arc-melted (test) and induction-melted (control) ingots were of the random type. The inclusion concentration was greatest in the test material; however, the inclusion size was smallest in the test material, thus reducing the overall inclusion density. The inclusions were also more uniformly dispersed in the test material from the outer surface to the center and from end to end of the rods.

6.3.2.2 Stringer Rating

The stringers found in the I & E rod samples in the induction-melted materials were longer, wider and more numerous than those in the arc-melted material.

In fact, stringers were almost nonexistent in samples taken from the rear of arc-melted rods. For consistency of evaluation, stringer ratings were obtained on the NPR stock; however, the low reduction ratio involved in the primary extrusion of these billets resulted in stringer data of very little value.

6.3.2.3 Grain Size and Recrystallization

The average grain size of the I & E rod stock for both types of material was 0.049 mm; however, the range of grain size was greater in the test material than in the control material.

Due to the erratic nature of the NPR grain size and the NPR and I & E recrystallization results, no comparison of the test and control materials could be made.

6.4 Reactor Testing

6.4.1 Savannah River Operation

Fuel cores from two arc-melted ingots and one control ingot were charged into a reactor at Savannah River. These cores were thermocycled three times. Upon completion of the reactor test, the following results were reported:

<u>Ingot No.</u>	<u>Test Type</u>	<u>Flow Decrease</u>
502	Arc-Melted	7.5%
505	Arc-Melted	2.9%
94333	Induction-Melted	2.3%

The flow decrease is the percentage of reduction in coolant flow in the outer channel caused by the swelling of the fuel cores of that channel. The channel containing the cores from Ingot 505 also contained cores from other sources (not from arc-melted ingots).

6.4.2 Hanford Operation

An order was received from Hanford for arc-melted and induction-melted control material suitable for coextrusion to NPR shapes. This order called for:

- a. Two high alloy ingots (one test and one control).
- b. Two arc-melted NOE billets (std. alloy).
- c. Two control NOE billets (std. alloy).
- d. Five arc-melted NIE billets (std. alloy).
- e. Two control NIE billets (std. alloy).

Hanford completed coextrusion cladding tests on Groups a through c and reported the following results:

<u>Ingot Type</u>	<u>Average Clad Variation (mils)</u>
<u>Arc-Melted</u>	
Standard Alloy - Ingot 1	4.2
Standard Alloy - Ingot 2	5.0
High Alloy - Ingot 1	5.4
	Average 4.9
<u>Induction-Melted</u>	
Standard Alloy - Ingot 1	4.2
Standard Alloy - Ingot 2	6.8
High Alloy - Ingot 1	8.0
	Average 5.6

These results all fall within the limits of acceptable clad variation. The average variation between groups is not significant, although there appears to be somewhat less variation with the arc-melted material.

In addition to the clad variation test, Hanford performed a metallographic evaluation on the high-alloy ingots. The results showed that fuel cores (before heat treatment) fabricated from the arc-melted billets had a considerably smaller band (or ring) of large grains around their OD than did the induction-melted non-heat-treated cores. The metallography of these two groups was similar in all other respects. The arc-melted material was not tested in a reactor.

7. CONCLUSIONS AND RECOMMENDATIONS

- 7.1. The arc melting of uranium into production-sized ingots (7 to 11 inches in diameter) of reactor grade is feasible.
- 7.2. The principal advantage of arc-melting uranium is the production of extremely fine, uniformly dispersed carbide particles. (The high arc temperature probably disintegrates large carbides in the electrode feedstock.) It is thought that the shallow pool of molten metal and the rapid solidification effectively eliminate the agglomeration or growth of nonmetallic particles. There is some evidence that these stable nonmetallics distributed throughout the fuel matrix fix grain boundaries and prevent fuel core swelling during irradiation.
- 7.3. Contaminants are better controlled in the arc-melting process. In fact, by eliminating the graphite ingot crucible, the source of erratic carbon contamination is avoided. Furthermore, in the work reported here, the hydrogen content was reduced slightly (0.3 ppm) by arc melting.
- 7.4. Arc melting did not result in any significant chemical refinement nor in the elimination of segregation if any had been present in the electrode. It should be noted, however, that the feedstock used for this test was within reactor-grade chemical specification prior to arc-

melting and that no chemical refinement was expected. Further work is required to determine the effects of arc melting on virgin materials.

- 7.5. Internal voids were formed during the solidification of the ingots. Such porosity has been reported as a frequent result of an unstable arc (glow discharge).⁷ Further experimental work is also required in this area of arc melting.
- 7.6. It is recommended that uranium be arc melted with fine dispersions of the stable compounds, UP, UC, UO₂, and UN and subjected to irradiation.
- 7.7. A program to determine the effects of the following variables on ingot quality and production rates is recommended:
1. Crucible-to-electrode size ratio.
 2. Power input and circuitry.
 3. Melting pressures.
 4. Control of the solidification pattern.
- 7.8. Arc melting could prove to be a valuable step in any continuous reduction, remelt, and casting route considered in the future.

8. REFERENCES

- ¹ H. M. Eikenberry and T. D. Nixon. Consumable-Electrode Arc-Melting of Uranium, USAEC Report NLCO-849. June 15, 1962.
- ² E. S. Noe and J. F. Schiltz. "Arc-Melting of Uranium Metal," Summary Technical Report for the Period January 1, 1959 to March 31, 1959, USAEC Report NLCO-785, p. 95. April 15, 1959. (Classified.)
- ³ E. S. Noe and J. F. Schiltz. "Evaluation of Arc-Melted Uranium Metal," Summary Technical Report for the Period July 1, 1959 to September 30, 1959, USAEC Report NLCO-795, p. 63. October 20, 1959. (Classified.)
- ⁴ E. W. Johnson, G. T. Hahn, and R. Itoh. "Characteristics of Consumable Electrode D. C. Arcs in Argon, Helium and Vacuum," Arcs in Inert Atmospheres and Vacuum, edited by W. E. Kuhn, p. 38. New York: Wiley, 1956.
- ⁵ H. M. Eikenberry and T. D. Nixon. *op. cit.*, p. 32.
- ⁶ M. H. Cornett. Metallurgy of Uranium: Procedures and Standards, USAEC Report NLCO-954. March 25, 1966.
- ⁷ W. H. Smith. "The Effect of Variables on the Melting Rate of Metals in the Consumable Electrode Arc Furnace," Arcs in Inert Atmospheres and Vacuum, edited by W. E. Kuhn, p. 49. New York: Wiley, 1956.

9. APPENDIX

TABLE VI Chemical Analyses of Electrodes and 7-Inch-Diameter Arc-Melted Ingots (ppm)

Ingot or Electrode	Carbon		Nitrogen		Hydrogen		Oxygen		Silicon		Iron	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
Electrode 33509	360	348	22	41	1.3	1.0	18	29	45	43	122	118
Ingot 533	343	614	20	60	1.1	1.3	20	35	47	48	131	136
Electrode 33512	462	383	24	36	1.0	1.1	9	20	42	31	120	122
Ingot 534	403	454	22	32	0.7	1.2	18	28	44	45	132	126
Electrode 33507	352	293	22	42	1.1	1.1	15	18	43	33	100	108
Ingot 535	330	382	30	35	0.8	1.2	17	31	45	46	108	115
Electrode 33510	333	469	18	29	1.6	1.9	24	25	41	35	118	119
Ingot 536	495	381	30	31	0.8	0.9	23	18	50	47	129	131
Electrode 33513	376	460	20	44	1.1	1.0	8	28	35	33	94	119
Ingot 537	357	439	25	34	0.9	1.2	14	19	42	47	117	101
Electrode 33505	306	326	26	27	1.4	1.0	15	25	53	48	106	110
Ingot 538	373	322	36	28	1.1	0.7	32	26	63	63	132	123
Electrode 33506	394	386	30	26	1.0	0.8	14	22	40	31	102	115
Ingot 539	390	408	31	40	1.0	1.3	16	47	42	46	98	103
Electrode 33514	351	425	25	50	1.4	1.3	16	17	42	32	128	128
Ingot 540	352	416	24	33	0.9	0.8	11	22	45	47	114	111
Electrode 33508	335	350	24	24	1.7	0.8	14	27	55	59	128	125
Ingot 541	325	465	20	31	1.4	0.6	19	23	49	56	144	146
Electrode 33511	390	414	21	22	0.8	1.0	12	18	43	51	122	124
Ingot 542	400	526	16	29	1.1	0.9	5	22	37	53	142	134

TABLE VII Chemical Analyses of Electrodes and 7 3/8-Inch-Diameter Arc-Melted Ingots (ppm)

Ingot or Electrode	Carbon		Nitrogen		Hydrogen		Oxygen		Silicon		Iron	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
Electrode 33520	359	385	24	53	1.4	1.5	9	8	39	31	110	113
Ingot 512	371	422	22	37	1.6	1.4	19	22	45	49	122	124
Electrode 33517	316	347	29	39	1.6	1.5	8	6	40	30	108	102
Ingot 513	335	374	29	41	1.1	1.5	20	29	45	45	113	113
Electrode 33521	409	421	35	20	1.1	1.1	16	19	36	31	120	115
Ingot 514	478	432	40	28	0.9	0.9	30	21	51	45	106	115
Electrode 33516	421	420	26	31	1.7	1.3	12	14	42	32	115	121
Ingot 515	416	433	29	38	1.2	1.5	15	17	46	47	127	126
Electrode 33519	402	395	31	22	1.3	1.1	14	17	39	31	112	107
Ingot 516	392	408	37	36	0.8	0.7	20	24	45	46	120	117
Electrode 33523	377	376	14	20	1.0	1.2	20	12	44	29	132	140
Ingot 517	373	387	25	31	1.0	0.9	21	21	48	55	151	146
Electrode 33525	445	415	21	31	1.2	1.1	22	16	42	34	117	115
Ingot 518	408	433	26	30	1.1	0.6	19	11	45	48	116	123
Electrode 33524	415	367	14	23	1.2	1.7	12	13	40	32	110	118
Ingot 519	358	390	21	25	1.0	0.9	23	27	42	48	127	133
Electrode 33522	397	379	25	20	1.4	1.0	18	13	41	31	114	117
Ingot 520	400	420	26	25	0.8	0.7	28	26	45	47	129	128
Electrode 33526	409	415	35	31	1.1	1.2	16	17	41	36	117	124
Ingot 521	359	402	57	24	1.1	0.9	19	12	42	11	150	159

TABLE VIII Chemical Analyses of Electrodes and 10-Inch -Diameter Arc -Melted Ingots (ppm)

Ingot or Electrode	Carbon		Nitrogen		Hydrogen		Oxygen		Silicon		Iron	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
Electrode 33475	554	553	58	15	0.65	0.6	26	27	70	66	109	114
Ingot 501	550	558	72	65	0.8	1.1	50	74	64	67	106	107
Electrode 33476	373	349	23	36	1.0	1.0	16	18	61	60	108	114
Ingot 502*	392	408	40	32	1.0	0.9	19	18	59	59	112	109
Electrode 33477	480	466	50	80	0.7	1.0	38	45	62	63	119	121
Ingot 503	464	496	78	62	0.8	0.6	42	24	61	70	116	120
Electrode 33479	660	725	50	81	0.8	0.5	50	42	83	85	158	159
Ingot 504	802	646	118	63	0.9	0.9	74	29	82	84	159	160
Electrode 33480	368	388	26	33	1.7	1.7	26	15	82	89	159	160
Ingot 505*	356	385	38	34	0.8	1.1	27	14	82	86	159	160

* Cores from these two Ingots were shipped to the Savannah River Operation for reactor testing.

TABLE IX Chemical Analyses of Electrodes and 11-Inch -Diameter, Arc -Melted Normal Ingots (ppm)

Ingot or Electrode	Carbon		Nitrogen		Hydrogen		Oxygen		Silicon		Iron	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
Electrode 33551	367	384	46	30	2.1	1.6	19	11	29	44	122	111
Ingot 506	370	381	36	26	0.6	1.1	19	23	49	45	142	138
Electrode 33553	339	335	30	23	1.2	1.0	12	9	40	29	117	117
Ingot 507	358	380	19	16	0.7	0.9	16	27	43	44	147	136
Electrode 33554	436	455	27	18	1.4	1.2	12	17	41	33	125	136
Ingot 508	436	450	21	23	0.8	0.8	15	20	49	48	133	137
Electrode 33552	385	294	22	30	1.0	1.7	18	17	36	27	108	115
Ingot 509	395	417	18	18	0.6	0.9	10	26	42	48	122	128
Electrode 33556	359	352	17	23	1.3	1.0	21	12	40	30	142	165
Ingot 510	377	394	21	21	0.6	0.6	12	12	41	45	157	139
Electrode 33555	381	384	25	14	1.8	1.5	18	25	39	30	118	127
Ingot 511	442	432	24	24	1.3	0.8	19	23	44	47	128	140

TABLE X Chemical Analyses of Electrodes and 11 - Inch - Diameter, Arc - Melted Enriched Ingots (ppm)

Ingot or Electrode	Carbon		Nitrogen		Hydrogen		Oxygen		Silicon		Iron	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
Electrode 31616	420	441	24	21	1.3	1.7	12	22	107	110	178	179
Ingot 522	430	430	22	28	0.8	0.8	27	27	109	97	177	154
Electrode 31615	417	460	16	17	1.1	1.3	14	22	100	97	166	167
Ingot 523	418	436	24	23	0.6	0.7	19	26	102	99	161	148
Electrode 31614	337	344	19	17	1.5	1.5	10	18	92	95	172	187
Ingot 524	348	377	26	24	0.9	0.8	14	19	90	90	172	172
Electrode 31612	402	412	19	21	1.0	0.8	16	29	103	99	210	168
Ingot 525	433	461	21	25	0.7	0.8	19	27	102	96	167	159
Electrode 31611	425	385	17	18	1.1	1.5	21	15	100	99	170	168
Ingot 526	433	434	21	26	1.2	0.9	15	23	102	96	167	160
Electrode 31610	386	358	17	15	1.5	1.2	14	48	97	100	176	179
Ingot 527	406	438	20	21	0.7	0.6	15	22	101	96	178	158

TABLE XI Variations in Chemical Analyses Within Ingots; 7 - Inch - Diameter Arc - Melted Ingots(ppm)

Ingot	Sample Location	Carbon		Nitrogen		Hydrogen		Oxygen		Silicon		Iron	
		Edge	Center	Edge	Center	Edge	Center	Edge	Center	Edge	Center	Edge	Center
Arc - Melted Ingot No. 536	Top	528	463	30	30	0.7	1.0	21	24	57	50	120	138
	2	469	455	38	36	0.6	0.7	30	45	50	45	138	141
	3	443	425	36	31	0.7	0.7	25	22	45	45	125	127
	4	365	382	26	23	0.5	0.9	26	27	47	49	126	143
	Bottom	391	374	28	33	0.8	1.1	21	16	47	46	144	119
Arc - Melted Ingot No. 538	Top	384	366	35	37	1.1	1.1	38	26	68	58	129	136
	2	352	363	40	39	0.7	1.0	34	14	60	59	119	129
	3	325	336	35	31	0.7	1.2	31	28	64	60	119	119
	4	276	307	36	30	0.8	0.9	19	21	63	59	120	126
	Bottom	286	300	28	27	0.6	0.7	30	23	66	61	128	118

TABLE XII Variations in Chemical Analyses Within Ingots; 7 ³/₈ - Inch - Diameter Arc - Melted Ingots(ppm)

Ingot	Sample Location	Carbon		Nitrogen		Hydrogen		Oxygen		Silicon		Iron	
		Edge	Center	Edge	Center	Edge	Center	Edge	Center	Edge	Center	Edge	Center
Arc - Melted Ingot No. 514	Top	492	463	42	38	0.9	0.9	32	28	52	49	106	105
	2	474	446	29	33	1.1	0.8	24	22	39	53	111	113
	3	439	428	23	29	1.3	1.1	23	21	44	44	125	122
	4	456	444	25	26	0.7	1.1	20	16	44	42	122	116
	Bottom	431	433	26	31	0.8	1.0	17	25	45	45	112	118
Arc - Melted Ingot No. 521	Top	363	355	94	21	1.1	1.1	21	17	41	43	150	151
	2	387	368	27	23	1.1	0.9	28	23	42	38	149	125
	3	367	360	19	33	0.5	0.8	29	18	43	38	138	128
	4	384	393	26	25	0.9	0.8	21	11	41	46	127	127
	Bottom	415	390	25	23	0.9	0.8	8	16	47	45	151	160

TABLE XIII Variations in Chemical Analyses Within Ingots;
10-Inch-Diameter Arc-Melted Ingots (ppm)

Ingot	Sample Location	Carbon		Nitrogen		Hydrogen		Oxygen		Silicon		Iron	
		Edge	Center	Edge	Center	Edge	Center	Edge	Center	Edge	Center	Edge	Center
Arc - Melted Ingot No. 501	Top	524	587	60	85	0.7	0.8	33	68	65	63	110	103
	2	547	631	86	45	0.8	1.0	28	27	67	66	108	109
	3	562	566	80	65	0.9	0.9	26	35	67	67	109	109
	4	568	537	68	41	0.7	0.8	29	22	66	66	109	110
	Bottom	560	556	62	68	0.7	1.5	28	120	67	67	107	108
Arc - Melted Ingot No. 503	Top	448	480	79	76	0.7	0.8	42	41	59	42	114	120
	2	520	493	74	73	0.7	0.8	52	30	61	41	117	113
	3	523	591	89	83	0.6	0.6	32	22	63	42	122	120
	4	513	492	77	45	0.5	0.7	22	28	61	43	118	119
	Bottom	489	503	74	49	0.6	0.5	20	27	66	47	120	127

TABLE XIV Variations in Chemical Analyses Within Ingots;
11-Inch-Diameter Enriched Ingots (ppm)

Ingot	Sample Location	Carbon		Nitrogen		Hydrogen		Oxygen		Silicon		Iron	
		Edge	Center	Edge	Center	Edge	Center	Edge	Center	Edge	Center	Edge	Center
Arc - Melted Ingot No. 523	Top	431	406	18	16	0.6	0.7	22	17	103	102	157	166
	2	429	404	21	24	0.8	0.7	22	29	100	97	169	156
	3	419	422	19	16	0.6	1.0	23	20	100	95	165	159
	4	423	410	23	23	0.6	0.7	31	26	100	96	163	151
	Bottom	430	422	21	25	0.7	0.7	26	26	99	99	140	156
Arc - Melted Ingot No. 531	Top	353	329	27	19	0.9	0.7	31	18	136	135	151	145
	2	363	350	23	31	0.7	0.7	19	20	130	127	151	143
	3	359	361	24	24	0.6	0.8	19	10	132	125	148	148
	4	357	363	25	21	0.7	0.8	13	6	130	124	144	145
	Bottom	347	370	23	22	0.7	1.0	20	14	128	129	151	146

TABLE XV Inspection Results; HAPO I & E Type O Fuel Cores
Produced from 7-Inch-Diameter Ingots

Arc-Melted Ingots						
Ingot No.	Pieces Inspected	Seams & Striations	Pits	Machining Nicks	Acceptable	% Yield
533	50	3	—	—	47	94
534	50	4	1	4	41	82
535	52	3	—	—	49	94
537	50	4	22	—	24	48
539	52	19	—	—	33	63
540	51	6	—	8	37	73
541	49	14	—	2	33	67
542	49	2	—	—	47	96
Totals	403	55	23	14	311	77

Overall Metal Quality Yield* 80%

Induction-Melted Ingots						
Ingot No.	Pieces Inspected	Seams & Striations	Pits	Machining Nicks	Acceptable	% Yield
66900	55	—	—	—	55	100
66902	55	—	—	—	55	100
66906	58	—	—	1	57	98
66908	58	—	—	1	57	98
66928	56	1	—	4	51	91
66929	57	3	—	8	46	81
66931	58	—	—	5	53	91
66933	57	6	—	1	50	88
Totals	454	10	—	20	424	93

Overall Metal Quality Yield* 98%

* This figure ignores losses due to machining.

TABLE XVI Inspection Results; SRP Mark VB Fuel Cores Produced From
10-Inch-Diameter Scalped Ingots

Arc-Melted Ingots						
Ingot No.	Pieces Inspected	Seams & Striations	Pits	Machining Nicks	Acceptable	% Yield
502	31	—	—	—	31	100
505	35	—	—	11*	24	69
Totals	66	—	—	11*	55	83

Metal Quality Yield** 100%

Induction-Melted Ingots						
Ingot No.	Pieces Inspected	Seams & Striations	Pits	Machining Nicks	Acceptable	% Yield
94328	26	—	—	1	25	96
94329	35	—	—	—	35	100
Totals	61	—	—	1	60	98

Metal Quality Yield** 100%

* Eleven cores were dropped in the pickling tank and were not retrieved.

** This figure ignores losses due to machining.

TABLE XVII Inspection Results; NPR Billets Fabricated From
11-Inch-Diameter Ingots

Arc-Melted Ingots				
	Ingot No.	Billet No.	Inspection Defects	Disposition
NOE Extrusions	522	F	Seams and Cold Shuts	Remelt
		G	Seams and Cold Shuts	Remelt
	524	F	Seams and Cold Shuts	Remelt
	525	F	Seams and Cold Shuts	Remelt
		G	Seams and Cold Shuts	Remelt
	532	F	Seams and Cold Shuts	Salvable
NIE Extrusions	526	F	In Specification	Class I
		G	Pits	Remelt
		H	Extrusion Defects and Porosity	Salvable
	527	F	Seams and Cold Shuts	Remelt
		G	Seams and Cold Shuts	Remelt
		H	Extrusion Defects and Porosity	Salvable
	529	F	Extrusion Defects and Cold Shuts	Remelt
		G	Extrusion Defects and Porosity	Salvable
	530	F	OD Borderline Dimension	Class II
	532	F	Seams and Cold Shuts	Salvable