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FABRICATION OF ALUMINUM-BASE IRRADIATION TEST PLATES

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ABSTRACT

We fabricated miniature test plates for the HFIR-ATR Fuel Irradiation Program. The cores of the plates were X8001 aluminum-alloy cermets with dispersoids of U_3O_8 and niobium-coated UO_2 -13% ZrO_2 and were clad with type 6061-O aluminum. The purpose of the program is to determine the influence of high-temperature irradiation to high burnup on the dimensional and chemical stability of the dispersions.

Both standard and instrumented plates are included in the program. Innovations in fabrication techniques were required for the instrumented plates, in which the fuel core consisted of two separate layers with provision for inserting a thermocouple in the aluminum between the cores. We developed a frame design and fabrication procedures to minimize the longitudinal offset that occurred between the two core layers during rolling.

Our final fabrication procedures, which simulated as closely as possible the technique developed for the HFIR and ATR, successfully produced the test plates with excellent dimensional control and no cracking of the niobium-coated UO_2 - ZrO_2 particles. These procedures and the results of preirradiation dimension measurements, fuel content and homogeneity measurements, metallography, and ultrasonic nonbond examination are presented in detail.

INTRODUCTION

The design of nuclear reactors tends consistently toward higher power densities, which in turn require higher concentrations of fuel materials. Usually the higher power density increases the maximum heat flux and maximum surface temperature of plate-type fuel elements. These changes dictate fuel plates of improved quality and performance characteristics.

The conceptual designs of the High Flux Isotope Reactor¹ and the Advanced Test Reactor² recognized the severe requirements on fuel materials and fabrication techniques that extend the present day limits on aluminum-base fuel plate technology. In fact, the levels of fission rate, heat flux, and temperature desired for these reactors were unexplored.

In irradiation to 8×10^{20} fissions/cm³ at approximately 180°F, both an aluminum-base dispersion containing 65% U₃O₈ and an alloy containing 48% U and some silicon performed satisfactorily.³ However, no data were available on irradiation performance at higher temperature. In a subsequent program, the Phillips Petroleum Company conducted an irradiation program with miniature fuel plates to test not only the U₃O₈-Al reference fuel for the ATR but also UO₂-Al and UAl₃-Al compositions as backup materials.⁴ These samples were ready for reactor tests by April 1963, and all irradiations were completed by the end of June 1963. To raise the in-reactor surface temperature to the levels expected in the ATR, the samples were coated, by anodizing, with an insulating layer of aluminum oxide. All of the fuel samples were dimensionally stable at maximum burnups of 7×10^{20} fissions/cm³, although metallographic examination showed reaction between the uranium oxide fuel particles and the aluminum matrix. The postirradiation examination also revealed that the plates containing 44% U₃O₈ or 41% UO₂ that had been irradiated to 1×10^{21} fissions/cm³ had blisters. Plates containing 54% UAl₃, which had the same ²³⁵U content and high atom burnup, did not blister. However, a good estimate of the temperature attained by the coated fuel plates was lacking in those experiments. After irradiation, the anodized film exhibited three general surface appearances - nonspalled, partially spalled over the entire core, and

¹F. T. Binford and E. N. Cramer, The High Flux Isotope Reactor, ORNL-3572, Vol. 1, A Functional Description (May 1964).

²D. R. de Boisblanc et al., The Advanced Test Reactor - ATR Final Conceptual Design, IDO-16667 (November 1960).

³A. E. Richt, C. F. Leitten, Jr., and R. J. Beaver, "Radiation Performance and Induced Transformations in Aluminum-Base Fuels," pp. 469-88 in Research Reactor Fuel Element Conference, September 17-19, 1962, Gatlinburg, Tennessee, TID-7642, Book 2 (1963).

⁴M. J. Graber et al., Results of ATR Sample Fuel Plate Irradiation Experiments, IDO-16958 (March 1964).

partially spalled over part of the core area leaving islands of non-spalled coating. Uncertainties in coating thickness, composition, and thermal conductivity make the assignment of a realistic temperature most difficult.

As a result of those tests, sufficient concern existed over the reference fuel materials for both the HFIR and ATR that a joint Phillips-ORNL irradiation program was established by the AEC. The commission also approved Phillips to construct a test facility in the ETR that would closely simulate the HFIR and ATR operating conditions. We included both standard and instrumented plates in the program. Each instrumented plate contains provision for inserting a thermocouple to monitor its center-line temperature. The purpose of this report is to describe in considerable detail the materials of construction and methods of fabrication for the miniature test plates prepared at ORNL and to record the preirradiation data measured at ORNL.

The ORNL fissile materials to be irradiated are particles of U_3O_8 and niobium-coated UO_2 -13% ZrO_2 , each dispersed in a matrix of X8001 aluminum and roll bonded at 500°C with alclad type 6061 aluminum. We explored the use of coated-particle fuel in aluminum dispersions primarily to minimize the chemical reactions that take place under irradiation between the oxide particles and the matrix. Within the experimental design, the concentration of uranium in the miniature cores, fabrication techniques, and testing parameters simulated the HFIR and ATR. To make the test clearly applicable to these reactors, we also included B_4C in a small number of the standard plates.

PLATE SPECIFICATIONS

Design

The dimensional requirements for the fuel plates, as summarized in Table 1, were established by Phillips and represented desirable specifications. Type types of miniature plates were designed: a 0.050-in.-thick conventional sample fuel plate and a 0.150-in.-thick instrumented fuel plate. The instrumented plate contained two fuel cores separated with

Table 1. Summary of Pertinent Design Data

	Sample Plate	Instrumented Plate
<u>Dimensions, in.</u>		
Plate length	5.750 ± 0.003	5.750 ± 0.003
Plate width	1.250 ± 0.003	1.250 ± 0.003
Fuel core length	5.469 ± 0.062	5.250 ± 0.250
Fuel core width	1.000 ± 0.031	1.000 ± 0.031
Cladding thickness	0.015 ± 0.003	0.015 ± 0.003
Spacer thickness		0.100
Fuel core thickness	0.020 ± 0.003	0.010 ± 0.002
Total plate thickness	0.050 ± 0.001	0.150 ± 0.001
<u>Materials</u>		
Cladding		
Type of aluminum	Alclad 6061	Alclad 6061
Type of alcladding	1100	1100
Frame		
Type of aluminum	Alclad 6061	6061
Type of alcladding	1100	
Fuel core		
Number of cores per fuel plate	1	2
^{235}U content per fuel plate	$2.205 \pm 0.022 \text{ g}$	$2.205 \pm 0.022 \text{ g}$
Fissile compounds	U_3O_8 $\text{UO}_2\text{-ZrO}_2$ (Nb coated)	U_3O_8 $\text{UO}_2\text{-ZrO}_2$ (Nb coated)
Aluminum matrix	X8001	X8001

a 0.100-in.-thick aluminum spacer, which provided an inactive portion of the plate in which thermocouples could be inserted between the cores.

Important dimensions that are identical for the two types of plates are the 5.750-in. length, the 1.250-in. width, the 0.125-in.-wide inactive edge of aluminum, the 0.109-in. minimum end cladding, and the 0.015-in.

cladding thickness. Initially the tolerances on core length and plate thickness for both types of plates were set at $\pm 1/32$ in. and ± 0.003 in. respectively. The former proved to be an impractical range, especially for the instrumented plates, and was subsequently modified to the values shown in Table 1. X-ray attenuation measurements for total fuel loading necessitated a decrease in thickness variations among the plates to ± 0.001 in.

Core Composition

The sample and instrumented plates were both specified to contain 2.205 ± 0.022 g ^{235}U in the form of either U_3O_8 or niobium-coated UO_2 -15% ZrO_2 dispersed in type X8001 aluminum. As shown in Table 2, six core compositions were fabricated for the irradiation test. The fuel loadings and fissile compounds were selected on the basis of present and future applications to either the HFIR or ATR programs. For example, compositions B and C, which are not significantly different, simulated the U_3O_8 concentration in the ATR and in the outer-annulus fuel region in the HFIR.

Table 2. Core Composition for Sample and Instrumented Plates

Designation of Composition	Type of Plate	Core Materials ^a
A	Sample	41% U_3O_8
B	Sample	42% U_3O_8
C	Instrument	43% U_3O_8
D	Sample	56% Nb-coated UO_2 - ZrO_2 + 0.16% B_4C
E	Sample	63% Nb-coated UO_2 - ZrO_2
F	Instrument	64% Nb-coated UO_2 - ZrO_2

^aBalance, type X8001 aluminum.

Spheroidal UO_2 - ZrO_2 that had been coated with a 6- to 8- μ layer of niobium was selected as a potential fuel for future applications in aluminum-base high-performance reactors and used in compositions D, E, and F. Composition D also contained B_4C at the approximate poison

concentration of the ATR fuel plate and the filler portion of the inner-annulus HFIR fuel plate. The selection of niobium-coated $\text{UO}_2\text{-ZrO}_2$ was based on the following postulates for improved resistance to irradiation damage:

(1) Niobium-coated $\text{UO}_2\text{-ZrO}_2$ particles would resist stringering and fragmentation when incorporated into fuel plates by conventional powder-metallurgy and roll-bonding techniques.

(2) The niobium coating would improve the chemical compatibility of $\text{UO}_2\text{-Al}$ dispersions and minimize the migration and agglomeration of fission gases.

(3) The spheroidal shape would resist swelling of the individual fuel particles from fission-gas buildup.

Materials

Niobium-Coated $\text{UO}_2\text{-ZrO}_2$ Powder

The niobium-coated $\text{UO}_2\text{-ZrO}_2$ powder was supplied in two batches by the Nuclear Materials and Equipment Corporation at Apollo, Pennsylvania. Batch 1 was used in compositions E and F (see Table 2) for the miniature fuel plates; composition D contained batch 2. Chemical compositions and physical properties measured for the two batches of coated oxide are shown in Table 3.

U_3O_8 Powder

The U_3O_8 powder was supplied by the Union Carbide Nuclear Company Y-12 plant at Oak Ridge, Tennessee, and by the Kerr-McGee Oil Industries, Inc., Oklahoma City, Oklahoma. The Y-12 material, which is identical to the oxide used in the first power element of the HFIR, was used in compositions B and C; composition A contained Kerr-McGee U_3O_8 . Pertinent data on both types of oxide appear in Table 4.

B_4C Powder

The B_4C powder conformed to the high-purity grade of the Norton Chemical Company and analyzed 75.9% natural boron. The major impurities

Table 3. Properties of Niobium-Coated $\text{UO}_2\text{-ZrO}_2$ Powder

	Batch 1	Batch 2
Nb-coated $\text{UO}_2\text{-ZrO}_2$		
Uranium content, %	45.05	51.82
Niobium content, %	41.09	32.23 ^a
Zirconium content, %	5.72	6.58 ^a
^{235}U enrichment, %	93.18	93.16
Coating thickness, μ	8.0	6.9
Density, g/cm^3	9.17	9.242
$\text{UO}_2\text{-ZrO}_2$ substrate		
Crushing strength, lb	0.41	0.37
Density, g/cm^3	9.460	9.443
Uranium content, %	76.47	
Particle shape		
Percentage of particles with major axis < 1.5 $\times$ minor	99.7	98.0
Percentage of particles with major axis < 2 $\times$ minor	99.8	99.0
Sieve analysis, %		
+200 mesh		0.7
-200 +230 mesh	100	94.1
-230 mesh		5.2

^aCalculated from an assumed uranium content of 76.47% in the substrate.

were 0.1% Fe, 0.3% B_2O_3 , and traces (0.5% total) of Na, Ca, Al, Si, N, and H_2O . The particles were less than 44 μ in diameter, as determined by screening on U. S. Standard sieves.

X8001 Aluminum Powder

The type X8001 aluminum powder was supplied by the Reynolds Metals Company and conformed to Grade 1-701 for -100-mesh atomized material.

Table 4. Properties of U_3O_8 Powder

	Y-12 Plant	Kerr-McGee
Purity, %	99.9	
Uranium content, %	84.67	84.60
^{235}U enrichment, %	93.16	93.17
Moisture content, cm^3/g	< 0.03	
Density (toulene), g/cm^3	8.25	8.13
Density (helium), g/cm^3	8.12	
Surface area, ^a m^2/g	< 0.05	0.09
Particle shape	Irregular	Irregular
Particle size range, μ	150 to dust	150 to dust
Sieve analysis, %		
+170 mesh	0.6	0.5
-170 +200 mesh	21.7	12.7
-200 +230 mesh	28.3	31.6
-230 +270 mesh	8.0	12.0
-270 +325 mesh	27.6	36.2
-325 mesh	13.8	6.9

^aStatic BET krypton surface area.

In a standard sieve analysis, the -325 mesh fines accounted for 60% of the total size range. Impurity contents were limited to 0.001% B, 0.002% Cd, and 0.008% Li.

Fuel Plate Frame and Cladding

The wrought material for the fuel plate frames and cladding conformed to the standard specification for aluminum-alloy sheet and plate, ASTM Designation B208-61, with the following modifications:

1. The picture-frame material for sample plates was aluminum plate alloy 6061-0 that had been clad on both sides with aluminum alloy 1100. The thickness of alloy 1100 on each side was approximately 5% of the total thickness of the composite plate.

2. The frame material for the instrumented plates was aluminum plate alloy 6061-T6.

3. The cladding was aluminum plate alloy 6061-0 clad on one side with aluminum alloy 1100. The thickness of alloy 1100 was approximately 5% of the total thickness of the composite plate.

FABRICATION PROCEDURES

The essential operations required to fabricate the miniature fuel plates are: (1) weighing and blending the component powder for each fuel core, (2) pressing and, in some cases, machining the fuel compacts to the designed dimensions, (3) degassing the compacts, (4) assembling the cores within a welded billet, (5) cladding by roll-bonding, (6) annealing to soften and also test for blistering, (7) cold rolling to specified thickness, (8) heat treating to the "O" temper, (9) marking and shearing the plate, (10) machining to finished length and width dimensions, (11) inspecting and final cleaning, and (12) packaging for shipment. The specific details for these general procedures are described below and represent many of the methods that we developed and adopted for manufacturing HFIR and ATR fuel plates.^{5,6}

Component Design

The billets for the sample and instrument plates contain two cores as shown in Figs. 1 and 2, respectively. In the sample billets, the cores are separated by a distance of 2 in. in the direction parallel to rolling to permit the simultaneous fabrication of two plates. The cores also are separated in the instrument billet, but in the direction normal to rolling. Thus, one billet is required for each instrument plate.

⁵M. M. Martin, J. H. Erwin, and C. F. Leitten, Jr., "Fabrication Development of the Involute-Shaped High Flux Isotope Reactor Fuel Plates," pp. 268-89 in Research Reactor Fuel Element Conference, Sept. 17-19, 1962, Gatlinburg, Tenn., TID-7642, Book I (1963).

⁶D. O. Hobson, R. L. Heestand, C. F. Leitten, Jr., Fabrication Development of U₃O₈-Aluminum Composite Fuel Plate for the Advanced Test Reactor, ORNL-3644 (July 1964).

ORNL-DWG 64-7476R

Fig. 2. Instrument Fuel Plate Billet Assembly.

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Fig. 1. Sample Fuel Plate Billet Assembly.

Design dimensions for the sample and instrument billets are given in Table 8 of the Appendix, which also includes a list of the components and a description of the materials. The small differences in length and width of the fuel compacts, which are reflected in the cavity dimensions, are the result of different estimates of spread and densification for the various core compositions.

Compact Preparation

Although close control of the uranium content per plate dictates the preparation of powders for each fuel section, limitations of time and available equipment necessitated the partial use of master fuel compacts. Individual core sections were machined from the master compacts.

Conventional powder metallurgical techniques were employed to blend and press individual fuel compacts of compositions A and D and master fuel compacts of compositions B, C, E, and F (see Table 2). Precise quantities of the component powders, as shown in Table 5, were weighed separately, combined in a blending jar, blended 2 hr without a binder addition, and immediately compacted at a pressure of 22.5 tsi to highly dense rectangular shapes. The faces of the powder metallurgy die were lubricated with a solution of chemically pure stearic acid in carbon tetrachloride. Before the master compacts were machined and the fuel sections were assembled in the billets, the volatile constituents of the lubricant were removed by

Table 5. Weights of Component Powders for Fuel Compacts

Composition	Die Size (in.)	Weight, ^a g			
		U ₃ O ₈	Nb-coated UO ₂ -ZrO ₂	B ₄ C	X8001 Al
A	0.733 × 0.964	4.027			2.797
B	1.000 × 1.800	7.108			9.840
C	1.000 × 1.800	3.665			4.866
D	0.733 × 0.964		4.570	0.0128	3.620
E	1.000 × 1.800		13.511		7.884
F	1.000 × 1.800		6.929		3.970

^aTo ±0.001 g.

heating the compacts 2 hr at 550°C at a pressure less than 0.1 torr. Two rectangular core sections were then machined from each master compact. The corners of the core sections for the instrument plates and the sample plates that contained U_3O_8 from Y-12 were filed to a radius of $1/32$ in.

Billet Assembly

As illustrated in Figs. 1 and 2, each fuel plate billet required two cover plates and one frame in addition to the two fuel compacts. Cover plates were cold rolled from 0.160-in.-thick sheet and sheared. The frames for the sample plates were fabricated from 0.425-in.-thick plate by hot rolling to an intermediate thickness of 0.200 in., cold rolling to a finish thickness of 0.157 ± 0.001 in., and machining. The corners of the two windows in the frames were broached square for fuel sections of compositions A, D, and E and those for fuel sections of composition B were machined to include $1/32$ -in. radii. As shown in Fig. 2, the instrument-plate frames contained top and bottom depressions, with $1/32$ -in. radii at the corners, for accepting the fuel sections. These frames were machined from 1-in.-thick wrought plate.

To determine the integrity of the cladding materials and the alclad bond, we heated the cover plates and frames to 500°C in air for at least 85 min. Pieces that blistered were rejected.

Immediately prior to billet assembly, both surfaces of the frame and the alclad surface of each cover plate that contacts the frame were thoroughly cleaned by scratch brushing with a power-driven stainless steel brush. To provide an interference fit, the width and length of the compacts were designed to be essentially identical to the dimensions of the cavity in the frame. To assemble these components, we heated the frame to 500°C, slipped the cold compacts into the expanded frame cavities, and then allowed the frame to cool to room temperature. To provide excess material for densification during roll cladding, the compacts were 0.003 in. thicker than the frame.

The cover plates were attached to the edges of the frame by tungsten inert-gas welding. High-quality welds were not required, since the welds

needed only to prevent shifting of the billet components during the initial stage of the hot-rolling operation.

Composite Plate Fabrication

Hot Rolling

The assembled and welded billets were hot rolled in lots of four on a two-high Mesta mill equipped with 20-in.-diam $\times$ 30-in.-wide rolls. The roll faces were well lubricated with a mixture of one part SAE-90-weight oil to two parts kerosene at all times during hot rolling. Immediately after being welded and before the first mill pass, the billets were heated to $500 \pm 10^\circ\text{C}$ on a clean furnace hearth of stainless steel. The sample billets were placed in the furnace with either the top or bottom cladding in contact with the hearth. The billets for the instrument plates, however, were supported on their edges during preheating and reheating to ensure a uniform temperature through the thickness of the billets and thus allow equal amounts of work to be imparted to the two cores during rolling.

The hot-reduction schedules, based on mill settings, and the hot-finished thicknesses of the sample and instrument billets are shown in Table 6. Near the end of the schedules, the reductions per pass were diminished successively to minimize thickness variations within a plate. All billets were rotated 180° about their longitudinal and transverse axes and reheated between passes. On the final mill setting, the plates were fed twice through the mill without reheat and their thicknesses were immediately measured with a micrometer. Additional double passes were made, as required, to roll the sample plates to 0.0625 ± 0.0005 in. and the instrument plates to 0.187 ± 0.001 in.

After cooling, the hot-rolled plates were numbered consecutively, starting with 800 for the first plate processed. The consecutive plate numbers were prefixed with O-3 and O-4 to identify ORNL fuel plate containing U_3O_8 and coated $\text{UO}_2\text{-ZrO}_2$ respectively. The numbers, which were 1/2 in. high, were stamped on each plate in the inactive section at the end that had been fed first through the mill. Prior to being annealed, the plates were degreased in trichlorethylene vapor and sheared to remove

Table 6. Hot Reduction Schedules
for Sample and Instrument
Billets^a

Mill Setting	Reduction, %	
	Sample Billet	Instrument Billet
1	15.0	14.5
2	15.0	14.5
3	22.5	14.5
4	22.5	14.5
5	22.5	14.5
6	22.5	14.5
7	22.5	14.5
8	12.0	14.5
9	8.5	14.5
10	5.5	14.5
11		14.5
12		7.0
13		3.5

^aConditions: furnace temperature, $500 \pm 10^\circ\text{C}$; billet preheat, sample, 45 min and instrument, 100 min; reheat per pass, sample, 5 min and instrument, 15 min through mill setting 4, 5 min thereafter.

approximately 2 in. of excessive aluminum from the ends. The rolled sample billets were also sheared in half to separate the two fuel plates.

Softening Anneal

To remove stresses induced in the last few passes of the hot-rolling process and to test for blisters, the fuel plates were annealed for 1 hr at 500°C and then air cooled to room temperature. Plates that contained one or more blisters were rejectable. No plate exhibited blisters after either this anneal or the subsequent final heat treatment.

Cold Rolling

After visual inspection for blisters, the plates were cold rolled 20% on a two-high United mill equipped with 12-in.-diam $\times$ 14-in.-wide rolls

that were well lubricated with a mixture of two parts SAE-90-weight oil to one part kerosene. The entering ends of the plates were dipped into the oil mixture, as required, before insertion into the mill. At the completion of cold rolling, the plates were degreased in trichlorethylene vapor. With the core approximately centered, the ends were then sheared to yield a plate 12.0 in. long $\times$ 5.2 in. wide.

The cold-reduction schedules, based on mill settings, were identical for the sample and instrument plates. The first setting was for approximately 8.5% reduction, the next three for 3.5% each, and the final setting for 2.0%. Four passes were made at each mill setting; between passes, the plates were rotated 180° about their longitudinal and transverse axes to minimize thickness variations, which in any one plate were within ± 0.0002 in. The cold-finished thicknesses for the sample and instrument plates were 0.050 ± 0.001 in. and 0.150 ± 0.001 in. respectively.

Final Heat Treatment

To facilitate subsequent marking, machining, and assembly of the irradiation test elements, the composite plates must be flat within ± 0.003 in. and free of stresses induced in rolling. In the final heat treatment, the plates were flattened and annealed at 500°C under a static load of 0.3 lb/in.² between two 1-in.-thick platens of type 6061 aluminum. The plates were assembled in two stacks of equal height between the platens, inserted into a top-loading furnace at room temperature, and heated to 500°C at a rate of approximately 200°C/hr. After annealing for 2 hr at 500°C, the plates were furnace cooled to room temperature at a rate of 25°C/hr and again inspected for blisters. Plates that contained one or more blisters were rejectable.

Examination and Marking

After annealing and visual inspection, the plates were fluoroscoped with a 175-kvp machine to delineate the location of the fuel-bearing section. Lines for cutting the plates to 1 7/8 in. wide $\times$ 6 3/8 in. long, with the core approximately centered, were scribed on the numbered surface of each plate. The fuel plate numbers were then inscribed with a

Burgess Vibro-tool at a location just inside the scribe line at the same end of the plate.

The sample plates were sheared on the scribe lines. The ends and sides of the instrument plates were sawed off to avoid the possibility of breaks that may occur between the cladding and the core during shearing thick fuel plates near the core edge. After being sized, the plates were machined to establish two reference edges, at right angles to one another, for locating the position of the core to a precision of ± 0.005 in. Approximately 1.8 in. excessive aluminum was removed from the width and length of the plates. The position of the core was then determined from radiographs. A vernier caliper was used to measure accurately the location with respect to the machined edges. Prior to machining, the fuel plate number was again inscribed with the same identification and tool in numerals about $3/32$ in. high at the same plate end.

Machining

The sample and instrument plates were machined individually on a vertical milling machine equipped with a side cutting mill. First, each composite plate was sandwiched between $1/8$ -in.-thick aluminum backup plates of the same length and width. After the reference edges were aligned with the milling tool and the assembly was firmly fixed on the milling machine table with hold-down clamps, the longitudinal sides of the plates were machined to within approximately 0.125 in. of the core to yield a finish plate width of 1.250 ± 0.003 in. The clamps were then repositioned, as required, to machine the plate to the final length of 5.750 ± 0.003 in. Approximately equal amounts of aluminum were removed from each edge of the fuel plates. With the fuel plate number up, a $1/16$ -in. $\times 45^\circ$ chamfer was then milled on the numbered end in the right hand corner of the plate. After completion of the machining operation, the plates were degreased in trichloroethylene and the machined edges were lightly deburred by hand filing.

Inspections

All plates were inspected to ensure that bonding, specified total uranium content, and the specified dimensions in machining and rolling

had been achieved. The Nondestructive Testing Group evaluated the plates for continuity of ultrasound transmission, fuel homogeneity, and fuel loading. The length and width of the cores were measured from radiographs and recorded along with the positions of the cores with respect to the overall dimensions of the machined plates. The weights, thicknesses, and pycnometric densities of the fuel compacts and of the finished plates after pickling were measured. The average core thickness was then calculated from actual spread, densification, and elongation of the core.

Preparation for Shipment

Before and after the density determination, all plates were pickled at room temperature for 2 min in a solution 1 part 60% HF, 10 parts concd. HNO_3 , and 100 parts H_2O by volume and rinsed in warm water (100°F) for 3 to 5 min. Approximately 0.0001 to 0.0003 in. of aluminum was removed from the plate thickness in this final operation. The plates were then wrapped individually in tissue paper to prevent surface damage and packed in plywood boxes for shipment.

PREIRRADIATION MEASUREMENTS

The disposition and composition designations for 39 miniature plates sent to Phillips are shown in Table 9 of the Appendix. Eleven of these plates, including two with split cores, have been irradiated in the ETR in cycles 68 and 69; three additional sample plates will be exposed in cycles 70, 71, and possibly 72. Preirradiation measurements on these miniatures are described below, and tabulated results are in the Appendix.

Phillips fabricated and submitted to us 17 miniature plates, as described in Table 7, for uranium homogeneity and ultrasonic nonbond determinations; the results are included in the Fuel Evaluation and Nonbond Evaluation sections. Each was fabricated to a reduction ratio of 8. The 0.020-in.-thick core was clad with 0.015 in. alclad type 6061-0 aluminum. We supplied the cladding stock, matrix powder, and U_3O_8 for these plates but not the UAl_3 intermetallic compound.

Table 7. Sample Plates Prepared by Phillips

Composition Designation	Number Submitted to ORNL	Core Material ^a (wt %)
P-1	6	50 UAl ₃ , 0.19 B ₄ C
P-2	6	41 U ₃ O ₈ , 0.19 B ₄ C
P-5	5	55 UAl ₃ , 0.19 B ₄ C

^aDispersed in type X8001 aluminum.

Dimensions

Table 10 in the Appendix lists the dimensional inspection results for the 39 miniature plates and includes an estimate of average core thickness calculated as described below under Fabrication Parameters. All measurements were made with conventional techniques and equipment: (1) low-contrast radiographs for core outline, (2) dial verniers for length and width, (3) dial indicators for flatness, and (4) 0.250-in.-diam flat-anvil micrometers for thickness. The thickness profile along the longitudinal center line of the plates appears in Table 11 in the Appendix.

Fabrication Effects

The over-all fabrication effects of spread, densification, and elongation were determined for the core of each sample plate. Values for specific plates are given in the Appendix in Table 12. The instrument plates were not evaluated, since the densification for neither the top or bottom core could be nondestructively measured. The rolled-core thickness in Table 10 and the total reduction in core thickness in Table 12 were calculated from the following expression:

$$1 - R = t_f/t_o = (1 - S)(1 - D)(1 - E) ,$$

where

R = fractional reduction in total thickness

S = fractional spread = $1 - w_o/w_f$

D = fractional densification = $1 - \rho_o/\rho_f$

E = fractional elongation = $1 - \ell_o/\ell_f$

ℓ = length of dispersion

w = width of dispersion

ρ = density of dispersion

t = thickness of dispersion

Subscripts o and f designate the initial and final attributes respectively of the degassed fuel compact and fully annealed fuel core.

Metallography

Figures 3 and 4 depict respectively the general appearance of the U_3O_8 and Nb-coated UO_2 - ZrO_2 dispersions in (a) longitudinal sections, (b) transverse sections, (c) transverse edges, and (d) longitudinal ends. The degree of fragmentation and stringering of the dead-burned U_3O_8 particles, illustrated in Fig. 3, is characteristic of the irregularly shaped material when roll bonded with a hot reduction of 84% at 500°C and a cold reduction of 20%. The use of spherical coated particles of UO_2 - ZrO_2 solid solution, however, improved the particle integrity, as shown in Fig. 4. No degradation of the individual particles could be observed after the dispersions had been fabricated in an identical manner to the U_3O_8 cores. The spherical particles, however, are more inhomogeneously distributed than the finer U_3O_8 particles in dispersions of equivalent uranium loading. Below under Fuel Evaluation we shall quantitatively define uranium inhomogeneity. Figure 4 also shows that the niobium coat on UO_2 - ZrO_2 particles can be maintained during fabrication.

Arbitrarily, the criterion for a metallurgical bond is the presence of grain growth across the line of discontinuity of two mating surfaces. Figure 5 shows the bond-lines (a, b, and c) and the degree of bonding (d, e, and f) achieved in rolling the plates at 500°C. The thin layers between the cover plate and core or frame are aluminum alloy 1100, which

(a) LONGITUDINAL NEAR PLATE CENTER

(b) TRANSVERSE NEAR PLATE CENTER

(c) TRANSVERSE EDGE

(d) LONGITUDINAL END

Fig. 3. Appearance of U_3O_8 Dispersion in Standard Plates of Composition A (41 wt% U_3O_8 + X8001 Al).

(a) LONGITUDINAL NEAR PLATE CENTER

(b) TRANSVERSE NEAR PLATE CENTER

(c) TRANSVERSE EDGE

(d) LONGITUDINAL END

Fig. 4. Appearance of Coated $\text{UO}_2\text{-ZrO}_2$ Dispersion in Standard Plates of Composition D (56% Nb-coated $\text{UO}_2\text{-ZrO}_2$ + 0.16% B_4C in X8001 Aluminum). Original reduced 36%.

Fig. 5. Metallographic Structure of Transverse Sections from Standard Plates Showing Grain Growth Across Roll-Bonded Interfaces. (a,d) Nb-coated $\text{UO}_2\text{-ZrO}_2 + \text{B}_4\text{C}$ in X8001 Al dispersion-to-cladding bond. (b,e) $\text{U}_3\text{O}_8 + \text{X8001}$ Al dispersion-to-cladding bond. (c,f) Bond of alclad 6061 cover plate to alclad 6061 frame. (a,b,c) Etched 60 sec with 1% aqueous HF solution, bright field illumination. (d,e,f) Anodized 90 sec in 1.5% aqueous HBF_4 solution, polarized light illumination. Original reduced 3%.

had been previously bonded to alloy 6061 to form the initial cladding stock. As expected, no metallurgical bond existed at the vertical interface between the fuel core edge and the frame.

Physical Properties

The physical properties that were determined for the fuel dispersions and miniature plates during fabrication were weight, density, and total uranium content. The measurements for the instrument plates are not complete, since the thermocouple holes will be drilled between the split cores at the ETR site.

The available data, including two estimates for uranium content in terms of ^{235}U , are presented in the Appendix in Table 13. The loadings are directly calculated from compositions by weight from WCAE, where W is the weight of the degassed compact, C the charged concentration of the fuel material, A the uranium assay, and E the enrichment of the uranium in ^{235}U .

The x-ray attenuation values of fuel loadings in Table 13 were determined from continuous scanning x-ray techniques.⁷ However, we needed a calibration curve of uranium mass in milligrams per 5/64-in.-diam spot versus x-ray attenuation in chart divisions for the group of plates with each core material. We obtained this calibration using chemical analyses in conjunction with the calibration curve developed for HFIR evaluations. A total of 16 x-ray scans per plate, indexed precisely 0.0625 in., was recorded on chart paper. After determining the average chart reading for each scan, we read the uranium mass per 5/64-in. spot from the calibration curve and multiplied it by the proper traversed area for that scan. The sum of the uranium masses for the 16 scans was the total uranium content of the plate.

The two methods for determining fuel loading gave essentially identical results for plates fabricated from unmachined compacts. For plates containing machined compacts, the x-ray attenuation contents are undoubtedly

⁷B. E. Foster, S. D. Snyder, and R. W. McClung, Continuous Scanning X-ray Attenuation Technique for Determining Fuel Inhomogeneities in Dispersion Core Fuel Plates, ORNL-3737 (January 1965).

more accurate and are preferred. We estimate the accuracy of the determination to be within 1% of the assayed loading.

The density of the core in the fabricated plate was obtained from conventional pycnometer techniques and the expression

$$\rho_c = \frac{\rho_{Al} \rho_s W_c}{\rho_{Al}(W_a - W_s) - \rho_s(W_a - W_c)},$$

where:

ρ_c = density of rolled core, g/cm³

ρ_{Al} = density of aluminum cladding, 2.703 g/cm³

ρ_s = density of solution, g/cm³

W_c = weight of core in air, g

W_a = weight of plate in air, g

W_s = weight of plate in solution, g.

Fuel Evaluation

In addition to the total fuel determination described above, the uranium distribution within 18 ORNL plates and 14 Phillips plates was also evaluated from continuous-scanning x-ray attenuation techniques. Arbitrarily, inhomogeneity within ORNL plates was defined as one or more 5/64-in.-diam spots deviating more than $\pm 30\%$ from the nominal ^{235}U area density or 1-in. and longer lengths of 5/64-in.-wide regions in which the averaged fuel content deviated more than $\pm 10\%$. The Phillips plates appear to contain approximately 5% excess uranium, possibly because particle fragmentation affects the ORNL calibration. Thus, inhomogeneity in Phillips plates was based upon an average measured area density rather than the nominal value. Although this fuel loading may be questionable, we felt that the variations recorded for the plates were definitely indications of uranium inhomogeneity at the quoted levels.

Tables 14, 15, and 16 in the Appendix record the magnitude and location of deviating uranium concentrations for ORNL sample plates, instrument plates, and Phillips plates respectively. Plates P-1-591, P-2-597, and P-5-627 are not included in Table 16, since they were destructively examined to provide the calibration curves. The homogeneity scans for

all type "O" (ORNL) and "P" (Phillips) plates, along with more detailed data, are on file in the Nondestructive Test Laboratory at ORNL.

Nonbond Evaluation

All type "O" and "P" miniature plates were ultrasonically evaluated for nonbond by a through-transmission technique previously developed for inspecting ATR and HFIR fuel plates.⁸ Due to the irradiation schedule, standards were not developed for the miniatures. However, good approximation references were a HFIR standard containing a 1/16-in.-diam flat-bottom hole for the sample plates and a piece of type 6061 aluminum with a 1/16-in.-diam flat-bottom hole for the split-core plates. We note that these references serve only as good approximations because plates with different type cores can have different attenuation properties. We have found higher and more variable attenuation in plates containing oxide cores and little variation in UAl_3 dispersions. Hence, plates that highly attenuate ultrasound could be reported erroneously as containing a large amount of nonbonding.

The results of the ultrasonic inspection are recorded respectively for ORNL and Phillips plates in Tables 17 and 18 in the Appendix. Many of the ORNL plates have indications of nonbonding at either a core end or a core edge. Limited metallographic examination showed small (about 1/32-in.-wide) nonbonds just beyond the core at the frame-to-cladding interface on both a core-end and core-edge specimen. We deemed these defects acceptable for the irradiation tests. The ultrasonic traces for Phillips plates indicated good bonding for all of the P-1 group and for most of the P-5 group; however, the P-2 plates show indications that we suspected were nonbonds. As predicted, metallography showed no nonbonds in a P-1 and a P-5 plate.

Metallographic examination of specimens from a P-2 plate revealed small nonbonds near a core edge and a core end, but not nearly as large as had been indicated from the ultrasonic data. The fuel particles,

⁸K. V. Cook and R. W. McClung, Feasibility of Ultrasonic Detection of Nonbond in ATR Fuel Plates, ORNL-TM-888 (August 1964).

however, had stringered in both the transverse and longitudinal directions. Stringering causes higher and more variable attenuation of ultrasound as well as x-rays and increases the spurious rejection rate through reduced nonbond detection sensitivity. This effect was not known before metallographic examination, and the delivery schedule prohibited reinspection after metallography.

For future reference, "C" scan recordings (plan view) were made for each plate to show the coordinates of any detected nonbond indication. Sometimes we tested the effect of varying the sensitivity level, and more than one scan was recorded on a number of the plates. This information, along with complete inspection and equipment data, is on file in the Nondestructive Test Development Laboratory at ORNL.

SUMMARY AND CONCLUSIONS

1. The fabrication procedures developed and adopted for manufacturing standard and instrumented irradiation test plates are presented in detail. Results of preirradiation measurements for 39 test plates shipped to the Engineering Test Reactor at the National Reactor Testing Station in Idaho are described and recorded.

2. The instrumented fuel plate, which contains two cores with provision for inserting a thermocouple in the aluminum between them, can be fabricated by roll bonding techniques. To achieve the desired dimensional tolerances, however, we needed to design a frame for the rolling billet in which the region between the two cores was not an aluminum plug but was integral with the aluminum frame.

3. Niobium coating on spheroidal UO_2 -13% ZrO_2 particles can be maintained during roll bonding with a hot reduction of 84% at 500°C and a cold reduction in thickness of 20%. In the rolled plate, the fuel particles retained their shape and resisted degradation in the form of stringering and fragmentation.

4. Conventional techniques for fabricating aluminum-base dispersions distributed the U_3O_8 particles more evenly than the larger niobium-coated UO_2 - ZrO_2 spheres. The absence of fragmentation with the spheroidal particles increased the degree of inhomogeneity.

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APPENDIX

Table 8. Specifications for Instrument and Sample Billets

Type of Billet	Composition	Components of Billets	Number Required	Materials	Dimensions, in.		
					Length	Width	Thickness
Sample	A	Cover plate	2	Alclad 6061-F Al	7.000 ± 0.015	5.000 ± 0.015	0.120 ± 0.001
		Picture frame	1	Alclad 6061-F Al	7.000 ± 0.015	5.000 ± 0.015	0.157 ± 0.001
		Cavity	2		0.733 ± 0.002	0.961 ± 0.002	
		Fuel compact	2	41% U ₃ O ₈ , fully enriched, + X8001 Al	0.733 ± 0.001	0.964 ± 0.001	0.160 ± 0.001
Sample	B	Cover plate	2	Alclad 6061-F Al	7.000 ± 0.015	5.000 ± 0.015	0.120 ± 0.001
		Picture frame	1	Alclad 6061-F Al	7.000 ± 0.015	5.000 ± 0.015	0.157 ± 0.001
		Cavity ^a	2		0.742 ± 0.002	0.957 ± 0.002	
		Fuel compact ^a	2	42% U ₃ O ₈ , fully enriched, + X8001 Al	0.743 ± 0.001	0.960 ± 0.001	0.160 ± 0.001
Instrument	C	Cover plate	2	Alclad 6061-F Al	7.000 ± 0.015	5.000 ± 0.015	0.115 ± 0.001
		Split-core frame	1	Type 6061-T6 Al	7.000 ± 0.015	5.000 ± 0.015	0.926 ± 0.002
		Cavity ^a	2		0.719 ± 0.001	0.957 ± 0.001	0.078 ± 0.0005 ^b
		Fuel compact ^a	2	43% U ₃ O ₈ , fully enriched, + X8001 Al	0.720 ± 0.001	0.960 ± 0.001	0.081 ± 0.001
Sample	D	Cover plate	2	Alclad 6061-F Al	7.000 ± 0.015	5.000 ± 0.015	0.123 ± 0.001
		Picture frame	1	Alclad 6061-F Al	7.000 ± 0.015	5.000 ± 0.015	0.157 ± 0.001
		Cavity	2		0.733 ± 0.002	0.961 ± 0.002	
		Fuel compact	2	56% Nb-coated UO ₂ -ZrO ₂ , fully enriched, + 0.16% B ₄ C + X8001 Al	0.733 ± 0.001	0.964 ± 0.001	0.160 ± 0.001
Sample	E	Cover plate	2	Alclad 6061-F Al	7.000 ± 0.015	5.000 ± 0.015	0.125 ± 0.001
		Picture frame	1	Alclad 6061-F Al	7.000 ± 0.015	5.000 ± 0.015	0.157 ± 0.001
		Cavity	2		0.728 ± 0.002	0.965 ± 0.002	
		Fuel compact	2	63% Nb-coated UO ₂ -ZrO ₂ , fully enriched, + X8001 Al	0.729 ± 0.001	0.967 ± 0.001	0.160 ± 0.001
Instrument	F	Cover plate	2	Alclad 6061-F Al	7.000 ± 0.015	5.000 ± 0.015	0.115 ± 0.001
		Split-core frame	1	Type 6061-T6 Al	7.000 ± 0.015	5.000 ± 0.015	0.926 ± 0.002
		Cavity ^a	2		0.717 ± 0.001	0.954 ± 0.001	0.078 ± 0.0005 ^b
		Fuel compact ^a	2	64% Nb-coated UO ₂ -ZrO ₂ , fully enriched, + X8001 Al	0.718 ± 0.001	0.957 ± 0.001	0.081 ± 0.001

^a1/32-in. radius on corners of frame cavity and fuel compact.^bDepth of depression.

Table 9. Disposition of Miniature Plates Sent to Phillips

Plate Number	Composition Designation	Disposition
0-3-803	B	ETRC, irradiated in cycle 69, hot cell
0-3-804	B	ETRC, cut and mounted for cold metallography
0-3-805	B	Irradiated in cycles 68 and 69, hot cell
0-3-806	B	Irradiated in cycles 68 and 69, hot cell
0-3-807	B	ETRC
0-3-809	B	ETRC
0-3-810	B	ETRC
0-3-812	B	Irradiated in cycle 68, hot cell
0-3-815	B	Irradiated in cycles 68 and 69, hot cell
0-3-816	B	Being irradiated in cycles 70, 71, and possibly 72
0-3-817	B	ETRC
0-3-818	B	ETRC
0-3-820	B	ETRC
0-4-823	F	Irradiated in cycle 69
0-4-824	F	Open
0-3-825	C	Open
0-3-827	C	Irradiated in cycle 68
0-4-829	E	Open
0-4-830	E	Open
0-4-831	E	Open
0-4-832	E	Open
0-4-833	E	Open
0-4-834	E	Open
0-4-835	E	Open
0-4-836	E	Open
0-4-837	E	Cut and mounted for cold metallography
0-4-838	E	Open
0-4-840	E	Open
0-4-843	D	Irradiated in cycle 68, hot cell
0-4-844	D	Irradiated in cycles 68 and 69, hot cell
0-4-848	D	Irradiated in cycles 68 and 69, hot cell
0-4-852	D	Irradiated in cycle 69, hot cell
0-4-857	D	Open
0-4-858	D	Open
0-3-860	A	ETRC
0-3-864	A	ETRC
0-3-871	A	Being irradiated in cycles 70, 71, and possibly 72
0-3-872	A	Being irradiated in cycles 70, 71, and possibly 72
0-3-874	A	Cut and mounted for cold metallography

Table 10. Record of Dimensional Inspections

Plate Number	Plate Dimensions, in.				Effective Core Dimensions, ^c in.				Average Core Dimensions, ^d in.		
	Length ^a	Width ^a	Thickness ^b	Flatness ^a	Length	Minimum End Cladding	Width	Minimum Edge Cladding	Length	Width	Calculated Thickness
0-3-803	5.751	1.250	0.0507	±0.001	5.512	0.110	1.010	0.120	5.484	1.003	0.0203
0-3-804	5.751	1.250	0.0507	±0.001	5.515	0.115	1.006	0.113	5.473	1.002	0.0204
0-3-805	5.751	1.250	0.0507	±0.001	5.515	0.116	1.003	0.115	5.483	1.000	0.0202
0-3-806	5.751	1.250	0.0507	±0.003	5.509	0.118	1.003	0.115	5.484	1.000	0.0203
0-3-807	5.751	1.250	0.0507	±0.002	5.510	0.111	1.008	0.120	5.462	1.001	0.0203
0-3-809	5.751	1.250	0.0506	±0.006	5.518	0.110	1.027	0.105	5.472	1.000	0.0204
0-3-810	5.750	1.250	0.0507	±0.002	5.528	0.104	1.007	0.118	5.480	0.998	0.0204
0-3-812	5.750	1.250	0.0505	±0.001	5.550	0.090	1.005	0.110	5.470	1.002	0.0204
0-3-815	5.749	1.250	0.0502	±0.002	5.516	0.111	1.007	0.113	5.472	0.996	0.0203
0-3-816	5.750	1.250	0.0506	±0.003	5.529	0.102	1.002	0.119	5.495	1.000	0.0203
0-3-817	5.750	1.250	0.0507	±0.002	5.538	0.098	1.005	0.113	5.475	1.000	0.0204
0-3-818	5.750	1.250	0.0506	±0.002	5.520	0.113	1.007	0.118	5.498	0.999	0.0202
0-3-820	5.750	1.250	0.0505	±0.002	5.586	0.080	1.008	0.118	5.488	0.998	0.0204
0-4-823 ^e	5.749	1.250	0.149	±0.002	5.328	0.148	0.989	0.125			
0-4-824 ^e	5.750	1.250	0.149	±0.003	5.343	0.202	0.986	0.123			
0-3-825 ^e	5.748	1.250	0.149	±0.003	5.353	0.185	1.000	0.101			
0-3-827 ^e	5.750	1.249	0.149	±0.002	5.484	0.125	1.001	0.124			
0-4-829	5.751	1.251	0.0503	±0.001	5.460	0.141	1.010	0.116	5.350	1.004	0.0194
0-4-830	5.751	1.252	0.0504	±0.002	5.495	0.116	1.005	0.118	5.358	1.004	0.0197
0-4-831	5.751	1.251	0.0499	±0.002	5.525	0.086	1.010	0.118	5.399	1.008	0.0197
0-4-832	5.751	1.251	0.0500	±0.002	5.526	0.109	1.015	0.114	5.403	1.008	0.0197
0-4-833	5.751	1.251	0.0504	±0.001	5.530	0.101	1.010	0.119	5.368	1.007	0.0199
0-4-834	5.751	1.251	0.0505	±0.002	5.498	0.123	1.008	0.119	5.321	1.003	0.0198
0-4-835	5.751	1.252	0.0504	±0.001	5.510	0.101	1.008	0.117	5.329	1.004	0.0200
0-4-836	5.751	1.250	0.0505	±0.002	5.516	0.115	1.008	0.115	5.343	1.002	0.0197
0-4-837	5.751	1.251	0.0502	±0.002	5.452	0.144	1.007	0.116	5.345	1.003	0.0197
0-4-838	5.751	1.250	0.0504	±0.002	5.489	0.119	1.010	0.115	5.369	1.005	0.0199
0-4-840	5.751	1.251	0.0505	±0.001	5.478	0.130	1.012	0.111	5.327	1.003	0.0195
0-4-843	5.752	1.251	0.0505	±0.002	5.496	0.127	1.016	0.117	5.398	1.006	0.0204
0-4-844	5.752	1.251	0.0505	±0.003	5.500	0.119	1.017	0.113	5.373	1.009	0.0204
0-4-848	5.751	1.250	0.0504	±0.002	5.488	0.118	1.010	0.120	5.343	1.004	0.0207
0-4-852	5.751	1.250	0.0503	±0.002	5.475	0.121	1.024	0.110	5.357	1.008	0.0205
0-4-857	5.751	1.250	0.0504	±0.002	5.484	0.131	1.012	0.118	5.389	1.008	0.0204
0-4-858	5.751	1.251	0.0502	±0.002	5.525	0.112	1.017	0.114	5.403	1.010	0.0203
0-3-860	5.745	1.246	0.0505		5.568	0.080	1.042	0.044	5.255	1.004	
0-3-864	5.751	1.248	0.0504		5.495	0.058	1.019	0.037	5.456	1.013	
0-3-871	5.750	1.249	0.0505	±0.002	5.517	0.107	1.010	0.104	5.463	1.008	0.0204
0-3-872	5.732	1.248	0.0505	±0.003	5.484	0.108	1.011	0.110	5.467	1.008	0.0206
0-3-874	5.748	1.247	0.0504		5.572	0.074	1.015	0.108	5.449	1.010	0.0203

^a±0.001 in.
^b±0.0002 in.

^c±0.010 in.
^d±0.005 in.

^eInstrumented plates.

Table 11. Thickness Profile Along Longitudinal Centerline of Plates^a

Plate Number	Thickness (mils) at Each Distance from Numbered Plate End						
	0.38 in.	1.00 in.	2.00 in.	3.00 in.	4.00 in.	5.00 in.	5.38 in.
0-3-803	50.8	50.8	50.8	50.8	50.8	50.8	50.8
0-3-804	50.8	50.8	50.8	50.8	50.8	50.8	50.8
0-3-805	50.8	50.8	50.8	50.8	50.8	50.8	50.8
0-3-806	50.8	50.8	50.8	50.8	50.8	50.8	50.5
0-3-807	50.7	50.8	50.8	50.8	50.8	50.8	50.5
0-3-809	50.8	50.8	50.8	50.8	50.7	50.7	50.5
0-3-810	50.8	50.8	50.8	50.8	50.8	50.8	50.8
0-3-812	50.5	50.6	50.6	50.7	50.7	50.6	50.5
0-3-815	50.5	50.3	50.3	50.3	50.3	50.3	50.2
0-3-816	50.7	50.7	50.7	50.7	50.7	50.7	50.6
0-3-817	50.9	50.8	50.8	50.8	50.8	50.8	50.8
0-3-818	50.8	50.8	50.8	50.8	50.7	50.6	50.6
0-3-820	50.6	50.7	50.7	50.7	50.6	50.6	50.5
0-4-829	50.5	50.5	50.4	50.3	50.3	50.3	50.2
0-4-830	50.5	50.5	50.5	50.5	50.5	50.5	50.4
0-4-831	49.9	49.9	50.0	50.0	50.0	50.0	50.0
0-4-832	50.1	50.2	50.2	50.2	50.2	50.0	50.0
0-4-833	50.6	50.5	50.5	50.5	50.5	50.5	50.5
0-4-834	50.6	50.6	50.6	50.6	50.6	50.6	50.5
0-4-835	50.5	50.4	50.4	50.5	50.5	50.5	50.5
0-4-836	50.6	50.5	50.5	50.6	50.7	50.8	50.6
0-4-837	50.4	50.5	50.4	50.3	50.3	50.2	50.3
0-4-838	50.6	50.5	50.6	50.7	50.5	50.5	50.5
0-4-840	50.7	50.8	50.6	50.7	50.5	50.6	50.6
0-4-843	50.7	50.6	50.6	50.5	50.6	50.5	50.6
0-4-844	50.7	50.7	50.6	50.6	50.4	50.5	50.6
0-4-848	50.6	50.5	50.5	50.5	50.4	50.4	50.4
0-4-852	50.4	50.4	50.4	50.4	50.4	50.4	50.3
0-4-857	50.5	50.5	50.5	50.5	50.5	50.4	50.5
0-4-858	50.4	50.3	50.3	50.3	50.3	50.3	50.3
0-3-860	50.6	50.5	50.7	50.6	50.7	50.6	50.6
0-3-864	50.4	50.4	50.6	50.5	50.6	50.6	50.5
0-3-871	50.6	50.6	50.5	50.5	50.7	50.6	50.5
0-3-872	50.8	50.6	50.6	50.6	50.5	50.5	50.5
0-3-874	50.5	50.5	50.4	50.5	50.6	50.5	50.6

^a All values are for unetched plates.

Table 12. Record of Overall Fabrication Effects

Plate Number	Change, %			
	Spread	Densification	Elongation	Total Reduction in Core Thickness
0-3-803	4.39	2.78	86.45	87.40
0-3-804	4.29	2.52	86.42	87.33
0-3-805	4.10	3.35	86.45	87.44
0-3-806	4.10	3.34	86.43	87.42
0-3-807	4.20	2.97	86.42	87.38
0-3-809	4.10	3.96	86.44	87.51
0-3-810	3.91	3.67	86.46	87.47
0-3-812	4.19	2.98	86.42	87.38
0-3-815	3.61	3.93	86.42	87.42
0-3-816	4.10	2.70	86.50	87.40
0-3-817	4.10	2.88	86.43	87.36
0-3-818	4.00	3.12	86.50	87.44
0-3-820	3.81	2.82	86.48	87.36
0-4-829	3.59	7.15	86.37	87.80
0-4-830	3.68	6.13	86.38	87.69
0-4-831	3.97	5.16	86.48	87.69
0-4-832	3.97	5.40	86.49	87.73
0-4-833	3.87	5.04	86.40	87.59
0-4-834	3.49	6.97	86.28	87.68
0-4-835	3.68	5.12	86.30	87.48
0-4-836	3.39	6.62	86.34	87.68
0-4-837	3.49	6.56	86.34	87.68
0-4-838	3.68	5.72	86.40	87.65
0-4-840	3.49	7.41	86.30	87.76
0-4-843	4.22	1.53	86.43	87.24
0-4-844	4.49	1.82	86.36	87.21
0-4-848	4.00	1.51	86.28	87.03
0-4-852	4.44	2.17	86.32	87.21
0-4-857	4.44	1.95	86.40	87.26
0-4-858	4.57	1.68	86.43	87.27
0-3-871	4.27	0.89	86.70	87.38
0-3-872	4.27	1.01	86.60	87.30
0-3-874	4.46	0.77	86.81	87.49

Table 13. Record of Physical Properties

Plate Number	Fuel Plate		Fuel Dispersion		^{235}U Loading, g	
	Weight ^a (g)	Density ^b (g/cm ³)	Weight ^a (g)	Calculated Density (g/cm ³)	Direct Calculation	X-Ray Attenuation
0-3-803	17.734	2.991	6.657	3.636	2.202	2.217
0-3-804	17.697	2.986	6.622	3.615	2.191	2.207
0-3-805	17.740	2.990	6.617	3.638	2.189	2.241
0-3-806	17.636	2.986	6.594	3.621	2.181	2.210
0-3-807	17.677	2.990	6.612	3.633	2.187	2.206
0-3-809	17.708	2.993	6.657	3.640	2.202	2.197
0-3-810	17.689	2.990	6.640	3.628	2.197	2.213
0-3-812	17.648	2.986	6.612	3.619	2.187	2.213
0-3-815	17.581	2.991	6.581	3.642	2.177	(c)
0-3-816	17.703	2.986	6.631	3.623	2.194	(c)
0-3-817	17.771	2.991	6.655	3.641	2.201	(c)
0-3-818	17.683	2.984	6.591	3.621	2.180	(c)
0-3-820	17.679	2.986	6.619	3.621	2.190	(c)
0-4-823	(d)	(d)	8.465		2.259	2.267
0-4-824	(d)	(d)	8.429		2.249	2.226
0-3-825	(d)	(d)	6.563		2.224	2.200
0-3-827	(d)	(d)	6.553		2.220	2.213
0-4-829	19.672	3.327	8.324	4.867	2.215	(c)
0-4-830	19.821	3.349	8.527	4.910	2.269	(c)
0-4-831	19.545	3.337	8.478	4.822	2.247	(c)
0-4-832	19.690	3.351	8.568	4.872	2.271	(c)
0-4-833	19.837	3.351	8.612	4.884	2.283	(c)
0-4-834	19.791	3.335	8.401	4.865	2.227	(c)
0-4-835	19.745	3.334	8.488	4.841	2.250	(c)
0-4-836	19.815	3.314	8.420	4.882	2.232	(c)
0-4-837	19.580	3.334	8.280	4.798	2.195	(c)
0-4-838	19.824	3.278	8.513	4.839	2.257	(c)
0-4-840	19.509	3.330	8.042	4.708	2.132	(c)
0-4-843	19.245	3.253	8.178	4.503	2.199	2.199
0-4-844	19.212	3.253	8.152	4.506	2.192	2.199
0-4-848	19.154	3.256	8.169	4.503	2.197	2.187
0-4-852	19.087	3.259	8.166	4.508	2.196	2.197
0-4-857	19.194	3.256	8.187	4.504	2.202	2.200
0-4-858	19.187	3.257	8.187	4.503	2.202	2.192
0-3-860	17.482		6.794		2.195	
0-3-864	17.518		6.794		2.195	
0-3-871	17.694	2.998	6.785	3.638	2.192	(c)
0-3-872	17.644	2.997	6.760	3.627	2.184	(c)
0-3-874	17.537	2.998	6.786	3.637	2.192	

^a ± 0.001 g.^c Data available in unprocessed forms.^b ± 0.005 g/cm³.^d Values will be determined by Phillips after thermocouple holes are drilled.

Table 14. Record of Uranium Inhomogeneity Within ORNL Sample Plates^a

Plate Number	Average Area Density of ²³⁵ U (g/in. ²)	Scan Number	Scan Distance from Reference Edge (in.)	Length, in.		Number of Spots ^b	
				Above 110% of Nominal	Below 90% of Nominal	Above 130% of Nominal	Below 70% of Nominal
0-3-803	0.4327						
0-3-804	0.4320						
0-3-805	0.4388	9	0.6720	1			
0-3-805		13	0.9220	1			
0-3-806	0.4325					1	
0-3-807	0.4331						
0-3-809	0.4309						
0-3-810	0.4343	2	0.2265			1	
0-3-810		4	0.3515	1			
0-3-812	0.4335						
0-4-843	0.4346	1	0.1590		2 1/2		Many
0-4-843		2	0.2215		2	1(140)	1(60)
0-4-843		3	0.2840		1		1(64)
0-4-843		4	0.3465		1	1(140)	
0-4-843		5	0.4090	1 1/2	1	1(140)	
0-4-843		6	0.4715	3		1(140)	
0-4-843		7	0.5340	3		1(136)	
0-4-843		8	0.5965	3		1(140)	
0-4-843		9	0.6590	2, 1			
0-4-843		10	0.7215	1, 1		1(138)	
0-4-843		12	0.8465			1(140)	
0-4-843		13	0.9090		1		
0-4-843		14	0.9715		2		
0-4-843		15	1.0340		1, 2		1(66)
0-4-843		16	1.0965		Entire scan		Many

Table 14. (Continued)

Plate Number	Average Area Density of ^{235}U (g/in. ²)	Scan Number	Scan Distance from Reference Edge (in.)	Length, in.		Number of Spots ^b	
				Above 110% of Nominal	Below 90% of Nominal	Above 130% of Nominal	Below 70% of Nominal
0-4-844	0.4353	1	0.1590	3 1/2		1	
0-4-844		2	0.2215	1		1, 1(134)	
0-4-844		3	0.2840	2		3, 1(134)	
0-4-844		4	0.3465	1 1/2, 2		1	
0-4-844		5	0.4090	Entire scan			
0-4-844		6	0.4715	Entire scan		2	
0-4-844		7	0.5340	Entire scan		1	
0-4-844		8	0.5965	4 1/2		1	
0-4-844		9	0.6590	4 1/2		1	
0-4-844		12	0.8465		1		
0-4-844		13	0.9090		2		Many (60)
0-4-844		14	0.9715		4		Many (60)
0-4-844		15	1.0340		Entire scan		Many (60)
0-4-844		16	1.0965		Entire scan		Entire scan
0-4-848	0.4374	1	0.1590		4		
0-4-848		2	0.2215		1		
0-4-848		8	0.6590	1 1/2			
0-4-848		9	0.7215	1			
0-4-848		10	0.7840	1		1(134)	
0-4-848		16	1.0965		Entire scan		Many
0-4-852	0.4367	1	0.1690		4		Many (60)
0-4-852		2	0.2315		2 1/2		Some (64)
0-4-852		3	0.2940		1	2(130)	
0-4-852		4	0.3565		1, 1	1(134)	
0-4-852		5	0.4190	1 1/2	1	1(140)	

Table 14. (Continued)

Plate Number	Average Area Density of ^{235}U (g/in. ²)	Scan Number	Scan Distance from Reference Edge (in.)	Length, in.		Number of Spots ^b	
				Above 110% of Nominal	Below 90% of Nominal	Above 130% of Nominal	Below 70% of Nominal
0-4-852	0.4367	6	0.4815		1	1(138), 1(132)	
0-4-852		7	0.5440	1 1/2, 1		Some (140)	
0-4-852		8	0.6065	1 1/2, 1		Some (134)	
0-4-852		9	0.6690	2 1/2, 1		Some (134)	
0-4-852		10	0.7315	1 1/2		1(132)	
0-4-852		11	0.7940	3 1/2		1(132)	
0-4-852		12	0.8565	3			
0-4-852		13	0.9190	2			
0-4-852		14	0.9815	2			
0-4-852		15	1.0440		1 1/2		
0-4-852		16	1.1065		Entire scan		Many (50)
0-4-857		15	1.0440		1		
0-4-857		16	1.1065		Entire scan		Many (60)
0-4-858	0.4312	1	0.1690		Entire scan		5(60)
0-4-858		2	0.2315		1, 1		
0-4-858		6	0.4815			1(130)	
0-4-858		8	0.6065			1(140)	
0-4-858		10	0.7315			1(134)	
0-4-858		11	0.7940	1			
0-4-858		12	0.8565	1, 2		2(132)	
0-4-858		13	0.9190	1			
0-4-858		16	1.1065		Entire scan		Many

^aNominal surface density is 0.4328 g/in.².

^bValues in parentheses are estimated percentages of nominal.

Table 15. Record of Uranium Inhomogeneity Within ORNL Instrument Plates^a

Plate Number	Average Area Density of ²³⁵ U (g/in. ²)	Scan Number	Scan Distance from Reference Edge (in.)	Length, ^b in.		Number of Spots ^b	
				Above 110% of Nominal	Below 90% of Nominal	Above 130% of Nominal	Below 70% of Nominal
0-3-825	0.445	1	0.1790		Entire scan		Many (50)
0-3-827	0.437	1	0.1790		Entire scan		Many (60)
0-3-827		9	0.6790	1(111)			
0-4-823	0.466	1	0.1790		Entire scan (70)		Many
0-4-823		2	0.2415	2, 1		5(150)	
0-4-823		3	0.3040	Entire scan (115)			
0-4-823		4	0.3665	3(115)		3(135)	
0-4-823		5	0.4290	2(115)		2(135)	
0-4-823		6	0.4915	3(115)		1(150), 2(135)	
0-4-823		7	0.5540	2(118)		2(135)	
0-4-823		8	0.6165	4(115)		1(150), 5(135)	
0-4-823		9	0.6790	5(116)		10(132)	
0-4-823		10	0.7415	Entire scan (115)		1(140), 1(145), 5(135)	
0-4-823		11	0.8040	1(112), 1(115)		2(137)	
0-4-823		12	0.8665	1 1/2(116), 1(112)		1(140), 3(135)	
0-4-823		13	0.9290			1(155)	
0-4-823		14	0.9915			1(150)	
0-4-823		15	1.0540	1(111)	1(85)		
0-4-823		16	1.1165		Entire scan (50)		Many (50)
0-4-824	0.457	1	0.1790		Entire scan (80)		Many (60)
0-4-824		2	0.2415			1(150)	
0-4-824		3	0.3040	1 1/2(118)		1(150), 1(145), 1(135)	
0-4-824		4	0.3665	1(111), 2(120)		1(150), 4(135)	
0-4-824		5	0.4290	3(115)		1(145), 1(135)	
0-4-824		6	0.4915	4(115)		1(155), 1(132)	
0-4-824		7	0.5540	5(116)		1(155)	
0-4-824		8	0.6165	3(118), 2(115)		1(160), 1(135), 1(140)	
0-4-824		9	0.6790	3(118)		1(160)	
0-4-824		10	0.7415	2(120)		4(135), 1(150), 1(155)	
0-4-824		11	0.8040	1 1/2(115)		1(155), 1(145)	
0-4-824		12	0.8665	1 1/2(118), 1(115)		1(155), 2(132)	
0-4-824		13	0.9290	2 1/2(116)		1(145)	
0-4-824		14	0.9915	1(116)		1(160)	
0-4-824		15	1.0540	2(115)	1(85)	1(150), 1(135)	
0-4-824		16	1.1165		1(50)		Many (50)

^aNominal surface area density is 0.451 g/in.².^bValues in parentheses are estimated percentages of nominal.

Table 16. Record of Uranium Inhomogeneity Within Phillips Miniature Plates

Plate Number	Estimated Average Area Density of ^{235}U (g/in. ²)	Scan Number	Scan Distance from Reference Edge (in.)	Length, in.		Number of Spots ^a	
				Above 110% of Estimated Average	Below 90% of Estimated Average	Above 130% of Estimated Average	Below 70% of Estimated Average
P1-584	0.47						
P1-585	0.47						
P1-587	0.47						
P1-588	0.47						
P1-589	0.47	1	0.1250		Entire scan		
P1-589	0.47	16	0.0625		2 1/2		
P2-593	0.46						
P2-595	0.46	3	0.2660			1 (132)	
P2-595	0.46	7	0.5160			1 (132)	
P2-595	0.46	8	0.5785	1			
P2-595	0.46	9	0.6410	1			
P2-595	0.46	10	0.7035	1			
P2-598	0.46						
P2-599	0.46	8	0.5785	1			
P2-599	0.46	9	0.6410	1			
P2-599	0.46	10	0.7035	2			
P2-599	0.46	11	0.7660	2			
P2-599	0.46	12	0.8285	1			
P2-599	0.46	16	1.0785		1		
P2-601	0.46	16	1.0625		Entire scan		Entire scan
P5-621	0.50	7	0.5000	1			
P5-621	0.50	16	1.0625		Entire scan		Entire scan
P5-623	0.50	16	1.0625		Entire scan		Entire scan
P5-625	0.50	16	1.0625		Entire scan		Entire scan
P5-626	0.50	16	1.0625		Entire scan		Entire scan

^aValues in parentheses are percentages of estimated average surface density of uranium.

Table 17. Ultrasonic Evaluation of ORNL Miniature Fuel Plates

Plate Number	Remarks
0-3-803	One 3/8-in.-long indication along the core end opposite the plate number
0-3-804	Same as 0-3-803
0-3-805	No indication
0-3-806	No indication
0-3-807	Many intermittent indications along the entire length of both core edges
0-3-809	One 3/4-in.-long indication along the core end opposite the plate number
0-3-810	Many intermittent indications along the entire length of the core edge nearest the chamfered corner
0-3-812	Many intermittent indications along one-half of the core edge from the chamfered corner
0-3-815	"C" scans not required
0-3-816	"C" scans not required
0-3-817	"C" scans not required
0-3-818	"C" scans not required
0-3-820	"C" scans not required
0-4-823	One 5/8-in.-long indication along the core end opposite the number
0-4-824	Two indications of 1/4-in. and 5/8-in. length respectively along the core ends closest to and opposite the plate number
0-3-825	No indication
0-3-827	No indication
0-4-829	Many intermittent indications along the entire length of the core end closest to the plate number
0-4-830	Four spot indications along the core end closest to the plate number
0-4-831	Away from the numbered end, two indications of 1/8-in. and 3/8-in. lengths along the core edge nearest the chamfered corner of the plate. Also, one continuous indication along the entire length of the core end closest to the plate number
0-4-832	One continuous indication along the entire length of the core end closest to the plate number
0-4-833	Same as 0-4-832
0-4-834	Two indications of 1/8-in. and 3/8-in. lengths along the core end closest to the plate number
0-4-835	Same as 0-4-832. Also, spot indications within core area nearest to chamfered corner
0-4-836	Same as 0-4-832
0-4-837	Same as 0-4-835
0-4-838	Same as 0-4-832
0-4-840	One large 1/8-in.-wide indication along the entire length of the core end closest to the plate number
0-4-843	Small gouge on numbered side at center of plate
0-4-844	One spot indication at core end nearest plate
0-4-848	Two indications of 1/4-in. and 3/8-in. lengths respectively along the core ends closest to and opposite the plate number
0-4-852	No indication
0-4-857	Two 1/4-in.-long indications along the core ends at diametrically opposite corners
0-4-858	No indication
0-3-860	"C" scans not required
0-3-864	"C" scans not required
0-3-871	Many intermittent indications along the entire length of the core edge opposite the chamfered corner
0-3-872	Same as 0-3-871
0-3-874	"C" scans not required

Table 18. Ultrasonic Evaluation of Phillips
Miniature Fuel Plates

Plate Number	Remarks
P-1-584	No indications
P-1-585	No indications
P-1-587	No indications
P-1-588	No indications
P-1-589	No indications
P-2-593	Numerous indications
P-2-595	Numerous indications
P-2-598	Numerous indications
P-2-599	Numerous indications
P-2-601	Numerous indications
P-5-621	No indications
P-5-623	Two spot indications along the core end closest to the plate number
P-5-625	One 1/4-in.-long indication along the core end closest to the plate number
P-5-626	No indications

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